

LIBRARY OF THE
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

628

Ll65c

no. 57-58

ENGINEERING LIBRARY
CONF. ROOM



ENGINEERING

ENGINEERING LIBRARY

The person charging this material is responsible for its return on or before the **Latest Date** stamped below.

Theft, mutilation, and underlining of books are reasons for disciplinary action and may result in dismissal from the University.

UNIVERSITY OF ILLINOIS LIBRARY AT URBANA-CHAMPAIGN

ENGINEERING CONFERENCE ROOM

JUL 17 1971

JUN 18 1975

JUN 18 REC'D



Digitized by the Internet Archive
in 2013

<http://archive.org/details/effectofsludgech57wood>

0.57



CIVIL ENGINEERING STUDIES

SANITARY ENGINEERING SERIES NO. 57

THE EFFECT OF SLUDGE CHARACTERISTICS UPON THE FLOTATION OF BULKED ACTIVATED SLUDGE

ENGINEERING LIBRARY
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

CONFERENCE ROOM

By
ROBERT F. WOOD

ENGINEERING LIBRARY
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS 61801

Supported By
FEDERAL WATER QUALITY
ADMINISTRATION
TRAINING GRANT WP 128

THE LIBRARY OF THE
NOV - 5 1970
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS
SEPTEMBER, 1970

THE EFFECT OF SLUDGE CHARACTERISTICS UPON THE
FLOTATION OF BULKED ACTIVATED SLUDGE

BY

ROBERT FRANK WOOD
B.S. Engr., Walla Walla College, 1960
M.S., University of Texas at Austin, 1966

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Sanitary Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1970

Urbana, Illinois

Ilb5c
A. 57-58

Eugen

ENGINEERING LIBRARY

THE EFFECT OF SLUDGE CHARACTERISTICS UPON THE FLOTATION OF BULKED ACTIVATED SLUDGE

Robert F. Wood, Ph. D.
Department of Civil Engineering
University of Illinois

The bulking of activated sludges with its accompanying difficult solids separation is a problem which is commonly faced in waste treatment plants. The purposes of this study were:

1. to investigate some of the properties of bulked activated sludges and to relate the properties to the flotation behavior of the sludges and
2. to investigate the possibility of using the batch flux analysis as a method of predicting the results of the operation of continuous flow flotation units.

The effects of the carbon to nitrogen ratio, the nitrogen content, and the morphological characteristics of the sludge as well as the rheological properties, yield strength and plastic viscosity upon the flotation behavior of the sludges were investigated. The float solids concentrations and the interfacial rise rates obtained from a standard batch flotation test procedure were used to compare the flotation behaviors of the sludges. Of the sludge characteristics studied, the rheological properties correlated the best with the flotation behavior of the sludges. The rheological properties reflected the morphological characteristics of the microorganisms which made up the sludge floc.

The diameter of the flotation column, the initial depth of sludge in the column and the column filling time were found to influence the interfacial rise rates of the batch flotation tests. A retardation factor which

was dependent upon sludge concentration was found to exist in batch flotation tests. The pressure at which the saturation of the recycle water was carried out was found to greatly affect the batch flotation test results even though the air to solids ratio was constant.

The batch flux method of analysis was used to predict the float solids concentration obtained from a laboratory scale continuous flow flotation unit. This method accurately predicted the float concentrations obtained from the continuous unit in some cases but was not always consistent. The Talmadge and Fitch method was an unsatisfactory method for extending the flux curve to higher concentrations for the activated sludges used here.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Professors R. S. Engelbrecht, J. T. Pfeffer, R. I. Dick, B. B. Ewing and V. T. Chow for serving as members of his doctoral committee. To his thesis advisor, Doctor R. S. Engelbrecht, and to Doctors J. T. Pfeffer and R. I. Dick the author is deeply indebted for their suggestions, guidance and encouragement throughout the course of the research and in the preparation of this thesis.

The author also wishes to thank the following for helping to make this thesis possible:

Messrs. G. L. Shell and E. C. Cardwell and the Eimco Corporation for the use of the continuous flow laboratory scale flotation unit.

The Central Soya Co. for supplying the molasses which was used as the substrate in this study.

The Dixon Springs Agricultural Experiment Station for loaning the tank used as the aeration tank in the laboratory scale activated sludge unit.

Miss Chrysilis Rymas and Mr. Mike Smith for their assistance in the laboratory.

All personnel in the Sanitary Engineering Laboratory who have helped in one way or another toward the completion of this study. Especially thanks are given to Joe Matherly, laboratory manager, for his kind assistance.

Mmes. Ruth Worner, Mary Grahl, and Betty Wood for their help in the typing of the thesis.

The author wishes to acknowledge with thanks the financial assistance granted by the Federal Water Quality Administration, Department of the Interior, which made this work possible through Training Grant WP 128. Also

he wishes to thank Loma Linda University for its financial support which was granted in the form of a loan.

And last but by no means least the author wishes to thank his wife, Betty, for her love, encouragement, and understanding throughout this work as she performed the monumental task of caring for a husband and four children.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	x
I. INTRODUCTION	1
A. General	1
B. Purpose and Scope	3
II. LITERATURE REVIEW	5
A. Sludge Bulking	5
1. Effect of Food to Microorganism Ratio on Sludge Quality	9
2. Effect of Substrate Carbon to Nitrogen Ratios on Sludge Quality	9
B. Sludge Quality and Rheological Properties	12
C. Dissolved Air Flotation	12
III. EXPERIMENTAL EQUIPMENT AND PROCEDURES	17
A. Laboratory Activated Sludge System	17
1. Description of Equipment	17
a. Constant Head Box	17
b. Primary Settling Tank	19
c. Aeration Tank	19
d. Continuous Flotation Unit	20
2. Substrate	22
3. Operation	24
a. General	24

	Page
b. Procedure for Changing the Characteristics of the Activated Sludge	25
B. Batch Flotation Tests	26
1. General Procedure	26
2. Standard Batch Flotation Test Procedure	30
3. Comparison of Methods for Performing Batch Flotation Tests	31
4. Reproducibility of Batch Flotation Data	33
5. Effect of Column Filling Time on Interface Rise Rate .	34
6. Effect of Column Diameter on Rise Rate	36
7. Effect of Column Depth on Initial Rise Rate	42
8. Effect of Pressure of Saturation on Batch Test Rise Rates	44
9. Summary	49
C. Solids Flux Analysis	50
1. Procedure for Obtaining Data from Continuous Laboratory Flotation Unit	50
2. Procedure for Determining Quantity of Air Released . .	52
3. Procedure for Obtaining Data for Batch Flux Curves . .	55
D. Study of Rheological Properties	58
1. Description of Viscometer	58
2. Calibration of Viscometer	61
3. Experimental Procedure	67
E. Removal of Extracellular Polysaccharide	68
F. Analytical Procedures	71
1. Chemical Oxygen Demand	71
2. Organic and Ammonia Nitrogen	72

	Page
3. Suspended Solids Determination	72
4. Sludge Volume Index	73
5. Total Carbohydrate	74
6. Float Solids Concentration	75
7. Carbon to Nitrogen Ratio of Sludge Solids	75
8. Photomicrographs	77
IV. RESULTS AND DISCUSSION	78
A. Relationships Between Sludge Characteristics and Floatability	78
1. Shifts in Microbial Population	78
2. Effects of Percent Nitrogen and Carbon to Nitrogen Ratio of the Sludge Upon Flotation	84
3. Relationship Between the Presence of Extracellular Polysaccharide and Flotation Behavior	88
4. Rheology of the Activated Sludges	91
5. Relationship of Rheological Properties to the Morphology and Nitrogen Content of the Sludge	100
6. Relationship Between Rheological Properties and Flotation Behavior	104
7. Continuous Flotation Unit Performance	113
8. Summary	114
B. Batch Flux Analysis of Continuous Thickener Operation . . .	117
1. General	117
2. Comparison of Batch Flux Results with Laboratory Flotation Unit Data	118
3. Investigation of Possible Methods for Extending the Batch Flux Plot	125
a. Direct Pressurization	125
b. Talmadge and Fitch Method	126

4. Effect of Anaerobic Conditions Upon Flotation	127
5. Summary	129
C. Significance of Results	130
V. CONCLUSIONS	132
VI. SUGGESTIONS FOR FUTURE WORK	135
REFERENCES	136
APPENDIX	142
VITA	143

LIST OF TABLES

TABLE		Page
1	CHARACTERISTICS OF THE MOLASSES USED AS SUBSTRATE FOR THE CONTINUOUS FLOW LABORATORY ACTIVATED SLUDGE SYSTEM	23
2	REPRODUCIBILITY OF BATCH FLOTATION DATA	33
3	TYPICAL BLENDING SCHEDULE FOR $A/S = 0.0046$	59
4	C-H-N DATA FOR SEVERAL ACTIVATED SLUDGES	88
5	SUMMARY BATCH FLOTATION DATA	122

LIST OF FIGURES

FIGURE	Page
1. SCHEMATIC DIAGRAM OF THE CONTINUOUS FLOW LABORATORY ACTIVATED SLUDGE SYSTEM	18
2. SCHEMATIC DIAGRAM OF FLOTATION TANK OF LABORATORY CONTINUOUS FLOW UNIT	21
3. SCHEMATIC DIAGRAM OF THE BATCH FLOTATION TEST APPARATUS	27
4. TYPICAL BATCH FLOTATION CURVES	29
5. EFFECT OF COLUMN FILLING TIME ON RISE RATE	37
6. EFFECT OF CYLINDER DIAMETER ON INTERFACE VELOCITY	39
7. EFFECT OF COLUMN DIAMETER ON RISE RATE	41
8. EFFECT OF COLUMN DEPTH ON RISE RATE	45
9. DETERMINATION OF RETARDATION FACTOR	46
10. EFFECT OF PRESSURE OF SATURATION ON RISE RATE	48
11. SCHEMATIC FLOW DIAGRAM OF THE CONTINUOUS FLOW LABORATORY ACTIVATED SLUDGE SYSTEM	51
12. APPARATUS USED TO MEASURE VOLUME OF GAS RELEASED FROM WATER UPON DEPRESSURIZATION	54
13. SCHEMATIC DRAWING OF COAXIAL CYLINDER ROTATIONAL VISCOMETER .	62
14. RELATIONSHIP BETWEEN VISCOSITY AND END EFFECT	63
15. VISCOMETER CALIBRATION CURVES	65
16. DETERMINATION OF END EFFECT	65
17. TYPICAL VISCOMETER DATA	69
18. STRING-OF-BEADS TYPE OF FILAMENTS	80
19. CARYOPHANON-LIKE FILAMENTS	80
20. CARYOPHANON-LIKE FILAMENT WITH CELLS ATTACHED PERPENDICULARLY TO THE AXIS OF THE FILAMENT	81

FIGURE	Page
21. ELONGATED FLOC	81
22. STIFF FILAMENT	82
23. RELATIONSHIP BETWEEN NITROGEN CONTENT OF THE SLUDGE AND FLOAT CONCENTRATION	85
24. RELATIONSHIP BETWEEN NITROGEN CONTENT OF SLUDGE AND RISE RATE	87
25. RELATIONSHIP BETWEEN CARBON TO NITROGEN RATIO AND FLOAT CONCENTRATION	89
26. RELATIONSHIP BETWEEN CARBON TO NITROGEN RATIO OF THE SLUDGE AND RISE RATE	90
27. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND EXTRACELLULAR POLYSACCHARIDE	92
28. RELATIONSHIP BETWEEN EXTRACELLULAR POLYSACCHARIDE AND FLOAT CONCENTRATION	93
29. RELATIONSHIP BETWEEN EXTRACELLULAR POLYSACCHARIDE AND RISE RATE	94
30. TYPICAL YIELD STRENGTH VALUES FOR ACTIVATED SLUDGE	95
31. FLOC CONTAINING LARGE FILAMENTS RESEMBLING CARYOPHANON	97
32. FLOC CONTAINING FLEXIBLE FILAMENTS	97
33. NORMAL ZOOGLEAL FLOC	98
34. TYPICAL PLASTIC VISCOSITY PLOTS FOR ACTIVATED SLUDGES	99
35. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND YIELD STRENGTH	102
36. RELATIONSHIP BETWEEN THE CARBON/NITROGEN RATIO OF THE SLUDGE AND YIELD STRENGTH	103
37. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND PLASTIC VISCOSITY	105
38. RELATIONSHIP BETWEEN PLASTIC VISCOSITY AND THE CARBON TO NITROGEN RATIO OF THE SLUDGE	106
39. RELATIONSHIP BETWEEN SLUDGE YIELD STRENGTH AND FLOAT CONCENTRATION FOR BATCH FLOTATION TESTS	107

FIGURE

Page

40.	RELATIONSHIP BETWEEN PLASTIC VISCOSITY AND FLOAT CONCENTRATION	109
41.	RELATIONSHIP BETWEEN YIELD STRENGTH AND RISE RATE	111
42.	RELATIONSHIP BETWEEN RISE RATE AND PLASTIC VISCOSITY	112
43.	RELATIONSHIP BETWEEN SLUDGE YIELD STRENGTH AND FLOAT CONCENTRATION FOR CONTINUOUS FLOTATION UNIT	115
44.	METHOD OF DETERMINING LIMITING CONDITIONS	119
45.	TYPICAL BATCH FLUX PLOT FOR THE LABORATORY CONTINUOUS FLOTATION UNIT	121
46.	COMPARISON OF PREDICTED FLOAT CONCENTRATIONS WITH THE ACTUAL FLOAT CONCENTRATIONS OBTAINED FROM THE CONTINUOUS FLOW FLOTATION UNIT	123
47.	TALMADGE AND FITCH EXTENSION OF BATCH FLUX CURVE	128

I. INTRODUCTION

A. General

The success of the activated sludge method of waste treatment is dependent upon the ability of the mixed liquor suspended solids to remove soluble organic matter and in turn to be separated from the liquid which is to be discharged from the process as treated effluent. Normally this separation is accomplished by gravity in the secondary settling tanks which follow the aeration process. Bulked sludge is only one of a number of types of sludge which separate poorly. Sludge bulking results from the production of a sludge which is not amenable to gravity settling as commonly practiced. The settling rate and degree of compaction are so low that unless the treatment plant has been designed to operate under bulking conditions, solids will be lost in the final effluent and, as a result, the BOD and suspended solids removal efficiencies will be greatly reduced. There is, however, always a definite line of demarcation between the settled solids and the supernatant even with a bulking sludge (Pipes, 1967a). The principal problem is that the rate of separation is too slow.

Sludge bulking may be caused by many factors, only some of which can be controlled at the waste treatment plant. Factors which have been reported as having caused sludge bulking include the following: the food to microorganism ratio (F/M), the dissolved oxygen concentration in the aeration tank of the waste being treated, and even the temperature of the air being supplied to the aeration basin (Ingols and Heukelekian, 1940).

Flotation processes have been used for several decades in the mining industry for the purpose of concentrating ores. Dispersed air flotation, a

process which may use a variety of chemicals which act as aids in flotation, commonly is used. While the dispersed air flotation processes used in ore concentration are not generally economically applicable to the solution of sanitary engineering problems, the basic principles of flotation which govern that process are applicable to dissolved air flotation. Gaudin (1957), as well as other authors, has given an extensive treatment of the flotation theory.

In flotation processes air bubbles become attached to solid particles, oil globules or, when dealing with biological sludges, the sludge floc. The air-solid agglomerate, having a specific gravity less than that of the surrounding liquid, rises to form a foam-like layer at the surface. The floated material is then removed for further processing. Dissolved air flotation, a type of flotation not commonly used in ore processing operations, has been used in sanitary engineering practice primarily as a means of solids separation with certain industrial wastes and for thickening biological sludges. Only in a limited number of cases has it been used for the clarification of activated sludge mixed liquors. With this process, water is saturated with air at pressures greater than atmospheric and subsequently is passed through a pressure reducing valve thus reducing the pressure to atmospheric. Air in excess of that required for saturation at atmospheric pressure comes out of solution as very small bubbles (50μ - 100μ diam) (Katz and Geinopolos, 1963; Vrablik, 1959). The air-laden water is immediately blended with the solid containing waste water, bubble attachment takes place and the air-solid agglomerates float to the surface and are removed for further treatment.

B. Purpose and Scope

Sludge bulking is a problem which is frequently encountered in activated sludge treatment plants. Bulkied sludges are generally efficient in the removal of the organic material from the waste being treated but, because of their poor settling properties, they are difficult to separate from the liquid flow by gravity sedimentation as commonly practiced. Loss of the sludge particles in the final effluent lowers the efficiency of the treatment process as a whole. If the loss of solids is sufficiently great, the efficiency of substrate removal decreases due to the reduction in mixed liquor suspended solids, (MLSS). The reduction in MLSS causes the F/M to increase thus increasing the bulking problem. If the solids separation operation could be accomplished efficiently, sludge bulking would no longer be a problem.

Conceivably dissolved air flotation offers a means of obtaining the necessary solids separation for these difficult to settle sludges. This process has been used in industrial waste treatment practice for separating poorly settling materials as well as for separating substances which have specific gravities which are less than that of water. With this process the separation rate, is greater than for gravity sedimentation.

The general purpose of this research was to explore the possibility of using dissolved air flotation as a means of separating bulkied activated sludges. The specific objectives were:

1. to investigate the relationships between some of the characteristics of activated sludge and the flotation behavior of sludges, and,
2. to explore the possibility of using the solids flux method of analysis to predict the operational performance of a continuous flotation unit.

The first objective was accomplished using sludges grown in a laboratory continuous flow activated sludge system. Manipulation of the organic loading applied to the aeration tank and the amount of nitrogen supplied with the substrate were used to produce sludges having different characteristics. The sludge characteristics investigated included the carbon to nitrogen ratio (C/N), the nitrogen content, the amount of extracellular polysaccharide which could be stripped from the floc, the morphology and the rheological properties, yield strength and plastic viscosity. A standard batch flotation test procedure was used to evaluate the effects of the sludge characteristics upon flotation behavior.

The second objective was accomplished by comparing the values of float solids concentration predicted by the batch flux analysis with the actual float solids concentrations obtained from a continuous flotation unit. These comparisons were made using a laboratory scale unit. Before the data for the batch flux curves could be obtained, a series of experiments were performed to determine the effects of column diameter, column height and column filling time upon the rise rates of sludge in the batch flotation test.

II. LITERATURE REVIEW

A. Sludge Bulking

The sanitary engineering literature is replete with descriptions of sludge bulking problems associated with the activated sludge process. While many of the reports offer conflicting hypotheses as to the causes of the condition, there is general agreement that there are at least two common types of bulking which can be differentiated microscopically, i.e. zooglear or non-filamentous bulking and filamentous bulking.

Non-filamentous bulking is characterized by the production of a sludge which contains abnormally high amounts of bound water and consequently has a specific gravity very nearly equal to that of water. This type of sludge bulking is the least common and the most difficult to control (Sawyer, 1966). Bulking due to bound water is normally recognized when microscopic examination of a bulked sludge shows the absence of or the presence of very few filamentous organisms. Microscopic examination of this type of bulked sludge reveals that the particles are ragged and diffuse with relatively large surface areas (Smith and Purdy, 1936). Sludge volume index here is of little value in describing the degree of bulking (Pipes, 1967b).

Filamentously bulked sludges, as the name indicates, are in the bulked condition due to the presence of significant numbers of filamentous microorganisms. Filamentous bacteria or filamentous fungi may cause this condition to occur (Pipes, 1967a; Lackey and Wattie, 1940). Members of the following genera have been identified as causing bulking: Sphaerotilus, Bacillus, Beggiatoa, Nocardia, Thiotrix, Arthrobacter and Geotrichum (Pipes, 1967a, 1967b). Pipes (1968) has published an atlas of activated sludge types

which includes photomicrographs of many of the filamentous organisms mentioned above. Sludge volume indexes ranging between 100 and 2,000 ml/g have been observed as a result of this type of bulking (Pipes, 1967b; Kraus, 1949). A filamentously bulked sludge may appear under the microscope to be a mixture of filamentous growths and bacterial floc. The filaments are believed to provide physical support between sludge flocs and to increase the bouyancy of the flocs, thus preventing them from settling and compacting well.

Many factors have been designated as contributing to the bulking of sludge and encouraging the growth of filamentous organisms. Sawyer (1966) has listed the causes of sludge bulking as being related to the characteristics of the waste, to fluctuations in the concentration and volume of the waste, and to limitations placed upon the system by its design and operation. A number of the items listed in these categories will be discussed.

Waste waters containing considerable amounts of carbohydrates have often been involved in sludge bulking problems (Lackey and Wattie, 1940; Morgan and Beck, 1939; Smit, 1930). Simple soluble substrates such as sugars, amino acids and carboxylic acids which are readily metabolizable by most microorganisms favor the growth of filamentous organisms while complex insoluble compounds which have to be hydrolyzed before being metabolized have been reported to favor the growth of organisms which have good settling properties (Ingols and Heukelekian, 1940; Pipes, 1967b). Often wastes which are high in carbohydrate are deficient in nitrogen and phosphorus. Such deficiencies promote bulking (Greenburg, et al., 1955; Jones, 1965). While the nitrogen content of bacteria is about 10 to 12 percent of the dry cell weight, fungi contain only 4 to 6 percent nitrogen (Jones, 1965; Kaylor et al., 1963). This fact gives fungi the competitive advantage for growth on a nitrogen deficient

type of waste. For carbohydrates, carbon to nitrogen ratios of from 40 to 10 are given as promoting bulking (Ingols and Heukelekian, 1940). Both low and high F/M ratios appear to be frequent causes of sludge bulking even in nutritionally balanced wastes (Logan and Budd, 1955). Bulking at high F/M ratios is a common problem (Genetelli and Heukelekian, 1964; Tischler and Eckenfelder, 1968). Ford and Eckenfelder (1966), reported that in laboratory activated sludge units treating brewery waste, refinery waste and domestic sewage, F/M ratios above about 0.7 produced sludge bulking. A low pH waste will tend to cause filamentous bulking as fungi are able to grow at pH values which are low enough to affect the growth of most bacteria (Jones, 1966; Pipes and Jones, 1963). Pipes and Jones (1963) reported that Geotrichum candidum grows well in the pH range 3 to 9 while the normal range for the activated sludge process is pH 6 to 9. Sphaerotilus natans, a filamentous bacterium, commonly associated with bulking, is less tolerant of low pH values than are most of the other bacteria of the activated sludge biomass.

Low levels of dissolved oxygen in the mixed liquor due either to the method of operation or to inadequate aeration capacity have frequently been cited as causing bulking (Heukelekian, 1941).

The idea that low dissolved oxygen in the mixed liquor promotes the growth of filamentous organisms has recently been challenged by Bhatla (1967). His work with activated sludge treatment of Kraft paper mill wastes indicated that his plant operated well in a filamentously bulked condition with 2.0 to 3.0 mg/l dissolved oxygen in the aeration tanks. The settlability of the sludge improved as the mixed liquor dissolved oxygen concentration was decreased. Stale sewage and septic return sludge have also been reported as causing bulking (Heukelekian, 1941). Hot weather and the accompanying low flow conditions

which permit sewage to become stale are factors here. On the other hand, low temperatures, particularly below 10°C , have also been cited as causes of bulking (Ludzak et al., 1961).

Sphaerotilus natans has for many years been the organism most commonly associated with filamentous bulking (Ingols and Heukelekian, 1939; Greeley, 1945; Ruchhoft and Watkins, 1929). Studies conducted in recent years by Jones (1964, 1965) and Pipes and Jones (1963) have revealed that Geotrichum candidum, a member of the biomass of most activated sludge systems, may also cause filamentous bulking. While both organisms are obligate aerobes, they are capable of metabolizing substrates at much lower oxygen tensions than bacteria. Sphaerotilus is a higher bacterium while Geotrichum belongs to the class Fungi Imperfecti. In certain stages of growth the two filamentous organisms look considerably alike; and this, no doubt, is part of the reason why bulking caused by Geotrichum may have been credited to Sphaerotilus at various times.

Whenever sludge bulking due to filamentous organisms has occurred in waste treatment plants, the usual practice has been to initiate action designed to destroy the filamentous growths and relieve the bulking condition (Heukelekian, 1941; Tapleshay, 1945; Haseltine, 1938).

The activated sludge process can, however, be successfully operated in a bulking condition provided the plant has secondary clarifiers and sludge recirculation pumps of adequate capacity (Pipes, 1967a; Bloodgood, 1947; Kraus, 1963). When such a system is properly operated, an effluent containing less BOD and suspended solids is produced than is usually obtained with normal sludge (Haseltine, 1932; Heukelekian, 1941; Keefer, 1963). Bhatla (1967) reporting on experience with a 10 mgd plant treating Kraft mill waste indicated that, when the plant was operated in a bulking condition, BOD and suspended

solids removals were 5 to 10 percent greater than when operated in a non-bulking state. Tischler and Eckenfelder (1968) reported that in bench scale tests using glucose and phenol as substrates, sludges containing appreciable amounts of filamentous organisms had much higher rates of substrate removal than did the normal sludges. With aniline as substrate, the removal rates were similar for both kinds of sludges. Jones (1966) states that "in high carbohydrate (mainly monosaccharide) or sulfite waste liquor (low pH), filamentous microorganisms (Geotrichum in particular) will thrive and effectively remove COD. This system is rendered inefficient only if the final solid-liquid separation fails to provide the desired effect."

1. Effect of Food to Microorganism Ratio on Sludge Quality

In addition to the role which F/M plays in inducing bulking as previously mentioned, it also plays a part in determining the percentage of storage products in the microbial cells. Walters (1966) has shown in batch studies on sludges grown on glucose and yeast extract that F/M does influence the percentage of storage products in the MLSS. He found that, up to a F/M of 4.3, the newly synthesized storage products constituted an increasingly larger percentage of the cell weight. Beyond an F/M of 4.3 a greater percentage of the substrate was used for protein synthesis.

2. Effect of Substrate Carbon to Nitrogen Ratios on Sludge Quality

The carbon to nitrogen ratio (C/N) of the substrate has a marked effect upon the quality of the sludge which is produced. Based upon the work of Helmers et al. (1951) a BOD/N ratio of 20 is commonly accepted as being necessary to prevent nitrogen deficiencies. While bulking has been encountered at this ratio, it has also been shown that systems can successfully operate at BOD/N ratios up to 30 or more. Apparently with carbohydrates, a range of BOD/N ratios can be successfully employed.

Symons and McKinney (1957) have shown that in nitrogen deficient conditions the microorganisms in activated sludge produced excess extracellular polysaccharide which is apparently not biodegradable by the organisms which produce it. Although the proportion of active mass in the sludge decreases as nitrogen deficiency increases, it is possible to operate a stable system on a continuous basis under nitrogen deficient conditions. The available nitrogen is utilized for the production of amino acids as long as the supply lasts (Bechir and Symons, 1966). The remainder of substrate processed by the cell is converted to polysaccharide. The efficiency of COD removal falls off, however, as the percentage of nitrogen in the cell decreases. Bechir and Symons (1966) in a laboratory scale completely-mixed system showed about 97 percent and 92 percent soluble COD removals for sludges containing 10 percent and 5.5 percent nitrogen respectively. Neither sludge age nor sludge loading influenced the efficiency of soluble COD removal. This system did not involve a solids separation step, therefore there were no data presented regarding the solids separation properties of the sludge. Information was not given concerning the types of organisms present. Helmers et al. (1951) studied the microbial requirements for nitrogen and phosphorous in the treatment of some industrial wastes. They found that the rates of BOD removal were not reduced until the nitrogen content of the activated sludge fell below 7 percent of the weight of the volatile solids in the sludge. A sludge nitrogen content of less than 7 percent was indicative of a critical nitrogen deficiency in the substrate.

Walters (1966) working with activated sludges grown on glucose and yeast extract in batch units, found that for substrate COD/N ratios of 16.5 and 56.0 the sludges contained 9.8 and 36.9 percent carbohydrate respectively. The increase in carbohydrate was due to the formation of excess polysaccharide

In addition to the normal amount of carbohydrate storage products. The excess polysaccharide is relatively nonbiodegradable and does not serve as a storage product for use in endogenous respiration. Hoover and Porges (1949) have given the nitrogen content of activated sludge as being 12 percent as derived from the general formula $C_5H_7O_2N$. This value is based on cells in the endogenous phase. McWhorter and Heukelekian (1964) report the nitrogen contents of sludges in the presence of exogenous substrate to be 8 to 9 percent. The difference between these values can be attributed to the presence of storage products in the cells in the growth phase.

As was stated earlier, bacteria are reported to contain 10 to 12 percent nitrogen while fungi contain 4 to 6 percent (Jones, 1965; Kaylor et al., 1963). If the microbial seed contains fungi it would seem that the fungi should tend to predominate in a nitrogen deficient system. Genetelli and Heukelekian (1964b), however, reported that for sludges grown on different substrates but having a BOD/N ratio of 20 the nitrogen content ranged from 8.7 to 10.4 percent. On a glucose substrate having insufficient buffer capacity a fungi predominated which had a nitrogen content of 10.4 percent. On the same substrate only with more buffer capacity, Sphaerotilus containing 8.9 percent nitrogen became the predominating organism. Kaylor et al. (1963) in their work with atmospheric nitrogen fixation employed a filamentous sludge containing 3.8 to 5.4 percent nitrogen to obtain 90 to 93 percent COD removals on a number of simple substrates.

The carbon to nitrogen ratio of the substrate does influence the composition of the sludge produced. The proportion of the sludge which is active in substrate removal and the presence of extra amounts of polysaccharide, some of which is in the form of extracellular capsular material, are evidence of this. The types of organisms predominating in the sludge also

may be influenced by the amount of nitrogen available. These factors may well change the surface properties of the sludge and may have an effect upon the flotation characteristics of the sludge.

B. Sludge Quality and Rheological Properties

The rheology of activated sludge has been studied by Dick (1965). His data indicate that the physical characteristics of the sludge are reflected in the rheological properties, yield strength and plastic viscosity. Dick and Ewing (1967) have reported that bulked sludges possess much higher yield strengths than do "normal" activated sludges. They have indicated that measurements made using a viscometer are responsive to the physical nature of the activated sludge and that the rheological nature of filamentous sludges are very different from those of nonfilamentous sludges. Chakrabarti (1967) has shown that as the F/M ratio increased, the yield strength and plastic viscosity of the sludge also increased. For example, for laboratory sludges grown on domestic sewage primary effluent he reports, for MLSS of 2,500 mg/l, yield strengths of about 3.3×10^{-2} and 7.6×10^{-2} dynes/sq cm respectively for F/M ratios of 0.3 and 0.6 lb BOD/lb MLSS. Yield strength was also found to be dependent upon the concentration of solids.

C. Dissolved Air Flotation

Dissolved air flotation has seen its greatest use to date as a method of recovering solids and oils from a wide variety of industrial wastes. It has been used since the early part of this century in the pulp and paper industry for the recovery of pulp fibers from white water. Only in the past 10 to 15 years has it been used to any extent in the treatment of biological sludges. While this process has been used quite extensively for the thickening of activated sludges (Katz, 1958; Hurwitz and Katz, 1958; Ettelt, 1964;

Katz and Geinopolos, 1967), only in a very few instances has it been used as the primary means of solids separation in the activated sludge process. In one instance this process was used to clarify the mixed liquor of an activated sludge process which was treating fine chemical wastes from a pharmaceutical manufacturing plant (Horne et al., 1962). The flotation unit was fed a mixed liquor having a solids concentration of from 1,000 to 2,500 mg/l and was producing a float of 10,000 to 15,000 mg/l suspended solids. Effluent suspended solids were 600 to 900 mg/l. Reportedly, the high effluent solids and relatively moderate float concentration were due to the nature of the waste and certain operational problems. Data regarding the sludge volume index or other characteristics of the mixed liquor were not published.

Mulbarger and Huffman (1970) have recently reported the use of dissolved air flotation for mixed liquor solids separation at an activated sludge waste treatment plant in Prince William County, Virginia. Domestic sewage was treated at this plant. The activated sludge produced had a SVI of 58 ± 8 ml/g. Float solids concentrations between 3 and 5.5 percent were obtained while the effluent suspended solids ranged up to about 200 mg/l, depending upon the operating conditions. There appears to be no published literature on the use of dissolved air flotation for the separation of bulked activated sludges. Most of the data which are available regarding the flotation of biological solids have to do with activated sludge thickening.

Ettelt (1964) has presented data from his thickening work done at Chicago's Southwest Treatment Plant which indicate that as the SVI increases the initial rise rate of the sludge decreases. His data show that as the SVI increased from 70 to 120 ml/g the initial rise rate decreased from 0.78 cm/sec to 0.48 cm/sec. The percentage of sludge which was floated also decreased as SVI increased. It is important to note that the SVI values here were in the

range for "normal" sludge, not nearly as high as would be expected with badly bulked sludges.

The concentration of solids recovered in the float and the concentration of solids in the effluent are functions of the suspended solids of the feed, the retention time of the solids in the flotation unit and the air to solids ratio (Vrablik, 1959). A solids gradient exists in the vertical direction through the sludge layer with the sludge having the greatest concentration of solids being nearest the top (Katz, 1963). The concentration of solids near the top, increases as the solids retention time in the flotation unit increases.

The air to solids ratio (A/S), the weight ratio of air bubbles to suspended solids in the flotation cell, is controlled by the pressure at which aeration is carried out, the percent liquid recycle, the degree of saturation and the concentration of suspended solids in the feed. The rate of rise of the air-solids agglomerate is directly proportional to this ratio. Data showing the effect of recycle rate on rate of rise for recycle rates up to 300 percent have been presented by Katz (1958, 1959). The higher recycle rates have higher initial rise rates because of the increased amount of air available for flotation and the loss of resistance to flotation due to dilution of the sludge by the recycled liquid. Polyelectrolytes are sometimes used in sludge thickening to increase the float solids concentration and to reduce the solids loss to the effluent (Garwood, 1967; Katz and Geinopolos, 1967; Jones 1968). The use of polyelectrolytes has permitted flotation units to be operated at loadings more than double those which were possible without them while still obtaining a comparable float solids concentration.

The limited amount of information found in the literature regarding the design procedures employed in sizing dissolved air flotation units

indicated that the procedures used are largely empirical. Apparently the practice has been to correlate data from batch flotation and pilot plant tests with the performance data obtained from the previous operation of full scale units on sludges of somewhat similar characteristics to determine the size of the flotation unit for a particular application. Katz (1963) has stated that for flotation units which are to be used primarily for sludge thickening, the solids loading rate is the parameter which is used to determine the flotation unit surface area. The surface area is determined by assuming a solids loading rate. The area obtained is checked to be sure that a maximum desirable hydraulic loading rate has not been exceeded. Loading rates of from 10 to 20 lbs/sq ft/day have been reported when polyelectrolytes were not used (Katz and Geinopolos, 1967). Jones (1968) recommended the use of loading rates of 48 lbs/sq ft/day when polymers are used. Typical hydraulic loading rates were 1,150 to 1,440 gal/sq ft/day for activated sludges (Jones 1968). The procedure used to determine the other dimensions of the flotation unit was not described in the literature. These dimensions are probably determined by empirically applying the rise rate data obtained from batch flotation tests.

Katz (1963) also pointed out that when the flotation unit is to serve primarily as a clarifier, volumetric surface loading which is related to the separation rate of the air-solid particle, is the parameter upon which the design is based. No further information as to the procedure for design was found in the literature.

Mulbarger and Huffman (1970) based upon their work with a full-scale flotation unit serving as a clarifier in the separation of activated sludge solids proposed the use of the following expression in the design of clarification units:

$$\frac{C_o}{C_i} = \exp \frac{A/S}{\mu Q/A_h} \quad (1)$$

where

C_o = effluent suspended solids

C_i = influent suspended solids

A/S = air to solids ratio

μ = dynamic viscosity

Q/A_h = hydraulic loading rate

A limited amount of information on the use of flotation for the separation of microorganisms from their culture media was found in the microbiological literature. Froth and dispersed air flotation were the methods generally used. With these processes chemicals are added to alter the surface properties of the cells to be floated. Dobias and Vinter (1966) gave a summary of the literature relating to the flotation of microorganisms. Kalyuzhnyi et al. (1965), reported from their work with the flotation of yeasts that the biophysical composition of the flocculated yeast cells were determined by the polysaccharide portion of the cell. Cells containing the higher amounts of polysaccharide showed superior flotability. Likewise the percentage of the yeasts cells which were recovered by flotation was greater for the cells which had high bound water contents than for those yeasts having lesser amounts of bound water. The information found in the microbiological literature appears to have a bearing upon the separation of activated sludge by flotation only in that it provides some information regarding the cell surface characteristics which influence floatability. This information, however, does not appear to be directly applicable to the flotation process for activated sludges.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. Laboratory Activated Sludge System

The experimental work of this investigation required a system for culturing activated sludge in sufficient quantities so that sludge samples several liters in size could be removed for use in experiments without greatly upsetting the equilibrium of the system. A continuously fed system was preferred to a batch system because it would more nearly represent the operation of a full scale waste treatment facility. As bulked sludges were of primary interest, a solids separation device capable of providing separation of this type of sludge in a reasonable time was necessary. This requirement together with the fact that the effect of sludge characteristics upon flotation was to be studied resulted in the choice of dissolved air flotation as the means of solids separation to be employed.

A completely-mixed activated sludge system using dissolved air flotation in lieu of gravity sedimentation as a means of separating the activated sludge solids was chosen as the system to be used in this study. The equipment consisted of a constant head box for maintaining a constant flow of dilution water, a primary settling tank, an aeration tank, a flotation unit, a pump reservoir and additional pumps along with the necessary appurtenances. A schematic diagram of the system is shown in Figure 1.

1. Description of Equipment

a. Constant Head Box

A constant head box was used to control the flow of dilution water into the primary settling tank. This consisted of a small wooden

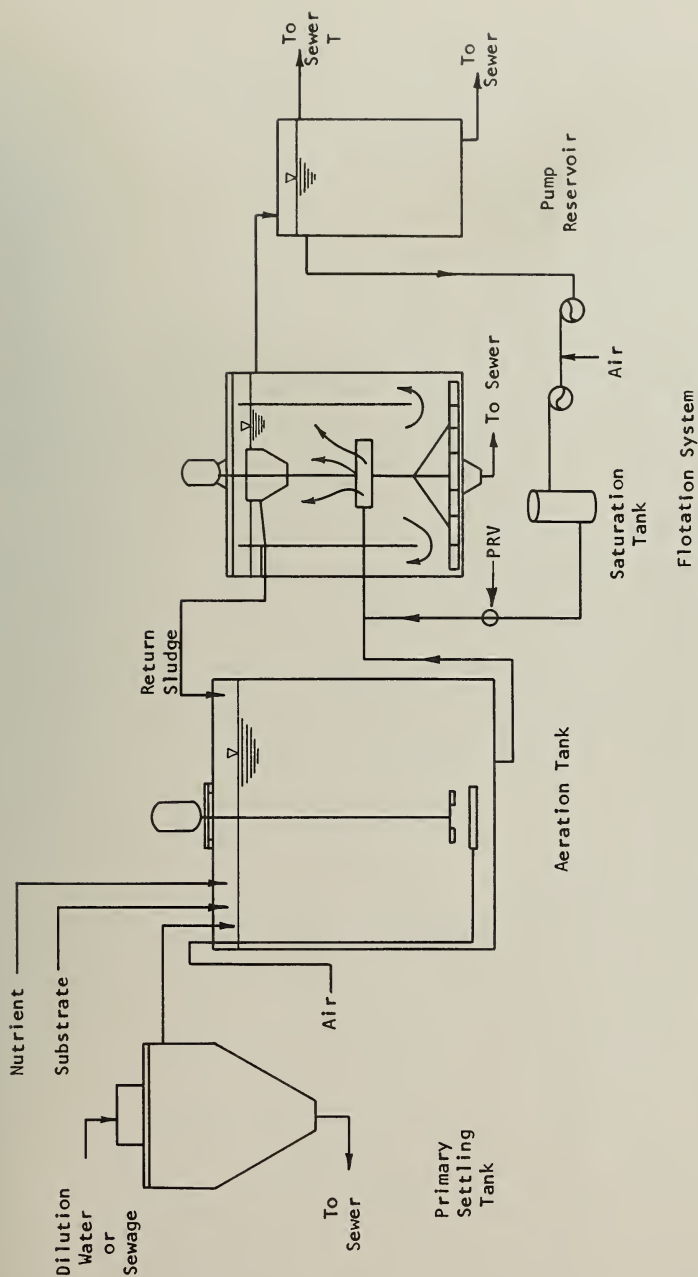


FIGURE 1. SCHEMATIC DIAGRAM OF THE CONTINUOUS FLOW LABORATORY ACTIVATED SLUDGE SYSTEM

box divided into two compartments by a wooden partition. Water or domestic sewage, depending upon the operational conditions, was introduced into one compartment. Inside this compartment the top end of a short length of 3.5 in. diam plexiglass column which was positioned vertically and sealed to the bottom of the box acted as a stationary weir. Excess water flowed over the weir and was discharged to the sewer. An adjustable 60° V-notch weir located in the partition between the two compartments controlled the rate of flow of liquid into the second compartment. From this compartment the water entered the primary sedimentation tank.

b. Primary Settling Tank

An aluminum tank painted inside with epoxy paint was used as a primary settling tank. The tank had a volume of about 120 gal which provided a detention time of 2 hrs at the nominal flow rate of one gpm. It is important that one point be clarified here. For most of the experimental work the flow through the tank was tap water. It was only during the few occasions when domestic sewage was fed instead of tap water that the primary settling tank served any real purpose.

c. Aeration Tank

A cylindrical sheet metal tank 54 in. diam and 54 in. high was used as the aeration tank. The tank, when filled to the operating level, held approximately 430 gal. The contents of the tank were mixed by the action of an 18 in. diam flat bladed turbine and the turbulence created by the rising of the air which was sparged beneath the turbine. The turbine was driven through a gear reduction box by a 0.5 hp electric motor which was mounted on a bridge across the top of the tank. The turbine was run at speeds ranging from 60 to 108 rpm. For the majority of the study, the speed was about 96 rpm. A leiman size 206 rotary oil-less

pressure pump,^{*} supplied air which was sparged under the turbine blade through a ring of perforated pipes. The combinations of turbine speed and air flow rate used were capable of maintaining the dissolved oxygen in the tank in excess of 2 mg/l under all the loading conditions which were used.

d. Continuous Flotation Unit

Solids separation was accomplished by a continuous dissolved air flotation unit on loan from the Eimco Corporation, Salt Lake City, Utah. The flotation unit consisted of two main parts, viz; the flotation tank where the actual flotation process took place and the system which saturated^{**} the recycle water. A diagram of the flotation tank is shown in Figure 2. The flotation tank consisted of a plexiglass tank 41.75 in. diam and 24 in. high. A circular plexiglass baffle which extended to within 6 in. of the bottom of the tank separated the flotation and clarification zones. The areas of the flotation and clarification zones were 3.3 and 5.5 sq ft respectively. A 1 in. tube conveyed the sludge and recycle water to the point of discharge which was located near the center of the tank and about 10 in. below the liquid surface. The water level in the tank was controlled by the height of the effluent weir. Four scrapers having adjustable skimming depths were used to skim the concentrated float into a collection hopper. Depths ranging between 0.5 and 3 in. were used at various times during the study. The speed of the scrapers could be varied by changing the pulleys on the driving motor and the gear reduction box. A speed of 0.25 rpm was most often used. When continuous skimming

^{*}Manufactured by Leiman Bros. Inc., East Rutherford, New Jersey

^{**}It should be pointed out that the word saturation as used in relation to the dissolved air flotation process is intended to mean only partial saturation of the water with air rather than complete saturation.

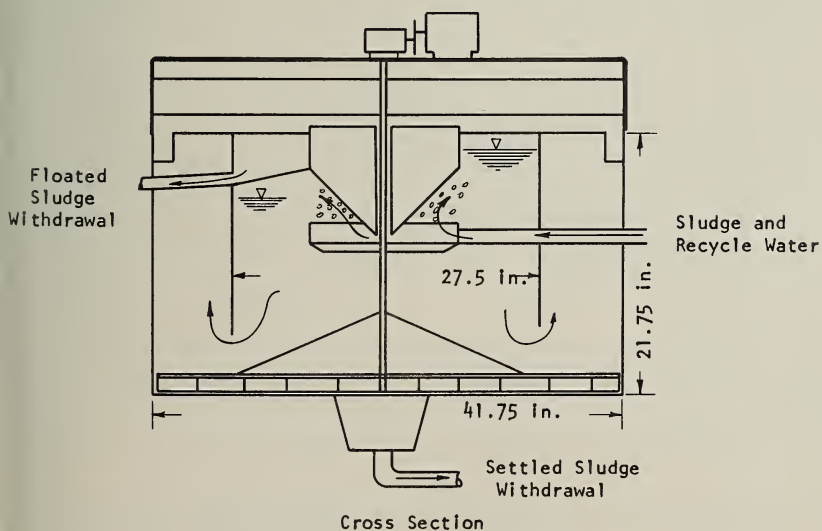
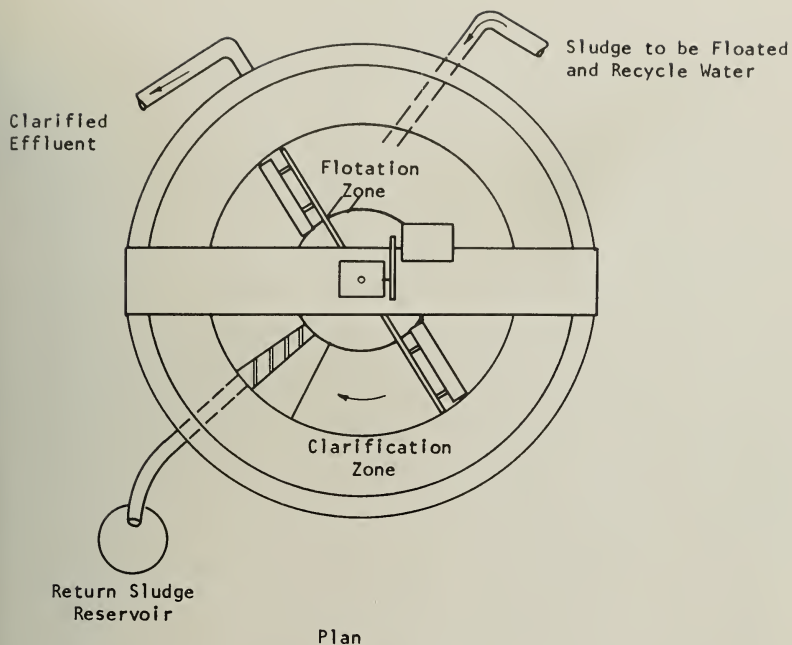


FIGURE 2. SCHEMATIC DIAGRAM OF FLOTATION TANK OF LABORATORY CONTINUOUS FLOW UNIT

was not desired, the frequency and length of the periods of collection could be controlled by a time clock. A small pump reservoir of about 3 liter capacity received the skimmed float. The collected sludge was returned to the aeration tank by a small float controlled pump.

The system used to saturate the recycle water consisted of two centrifugal pumps connected in series, an air compressor, a saturation tank, and a pressure reducing valve, plus the necessary valves and piping. The saturation process was carried out by injecting compressed air into the liquid stream at a point upstream of the second pump. The saturation tank was a 42 gal pressure tank which received the discharge of the second pump. The tank was equipped with a float controlled valve which discharged air to the atmosphere when the water level in the tank became too low. A 0.5 in. needle valve^{*} was used as a pressure reducing valve. The system was operated at 40 to 50 psig using flotation unit effluent as a recycle water.

2. Substrate

Since filamentously bulked sludges were of interest in this study, a substrate which was deficient in nitrogen was desired. Molasses, because of its high carbohydrate and low nitrogen content, was chosen as the substrate to be used in this study. Some of the characteristics of molasses are listed in Table 1.

Ammonium hydroxide and sodium monobasic phosphate were used to supply the nitrogen and phosphorous nutrients. The tap water which was fed continuously to the aeration tank as dilution water for the molasses was

^{*}Cat. No. 628-14, 0.5 in. needle valve, manufactured by Central Brass and Aluminum Company, Portland, Oregon

assumed to supply the other inorganic nutrients necessary for microbial growth.

TABLE 1
CHARACTERISTICS OF THE MOLASSES USED AS SUBSTRATE
FOR THE CONTINUOUS FLOW LABORATORY
ACTIVATED SLUDGE SYSTEM*

Constituent	Content
COD	1,040,000 mg/l**
BOD ₅	830,000 mg/l**
Crude protein	3 percent
Ca ⁺⁺	0.67 percent
Fiber	nil
Fat	nil
Ash	9.4 percent

* 1959 Feed Ingredient Analysis Table, Nopco Chemical Co.,
Newark, New Jersey

** Determined by the author

Because of its high BOD and viscosity it was necessary that the molasses be diluted before being fed to the aeration tank. The molasses was diluted to the desired concentration with tap water. Fifty-five gallon quantities of diluted molasses had to be made up every 2-3 days. In the early part of the study the ammonium hydroxide and sodium phosphate were mixed with the molasses. The substrate was pumped to the aeration tank at the desired rate using a Model T-8 Sigmamotor pump.* During the 2 to 3 days required to empty the feed drum some fermentation took place. In order to eliminate this problem, the feed system was revised. The molasses was diluted to a COD of 100,000 mg/l and the sodium phosphate added. The

* Manufactured by Sigmamotor Inc., Middleport, New York

mixture was refrigerated and fed directly to the aeration tank. The ammonium hydroxide in concentrations of about 100,000 mg/l $\text{NH}_3\text{-N}$ was pumped to the aeration tank separately by a Beckman Model 746 solution metering pump.* The point of discharge was located well below the liquid level to minimize the possibility of losing ammonia gas to the atmosphere.

3. Operation

a. General

The laboratory activated sludge system was operated on a continuous flow basis using the substrate previously described. The aeration tank was originally seeded with activated sludge obtained from the Champaign-Urbana Sanitary District's North-east plant. When the organic loadings to the aeration tanks were being changed in order to promote changes in the characteristics of the sludge, domestic sewage primary effluent was substituted for tap water to reseed the aeration tank. With the exception of a couple of brief occasions, the dissolved oxygen level in the aeration tank was maintained above 2 mg/l. The nominal dilution water flow rate was one gpm; however, on many occasions it was not possible to keep the system in operation at that flow rate due to the poor flotation characteristics of some of the sludges. In these instances the flow rate had to be substantially reduced.

The continuous flotation unit was operated using pressures of saturation between 40 and 50 psig. In the early part of the study the unit was viewed primarily as a means of accomplishing the solids separation necessary to keep the continuous system in operation rather than as a part of the experimental work. Changes were made in the operational

*Manufactured by Beckman Instruments Inc., Fullerton, California

settings as needed to maintain the continuous system. In the latter part of the work when comparisons were being made between the continuous unit's operation and the batch flotation data, the operation was closely controlled during the times when testing was underway.

b. Procedure for Changing the Characteristics of the Activated Sludge

The types and characteristics of the microorganisms which make up an activated sludge biomass can be influenced by a number of factors. Nutrient deficiencies, especially nitrogen deficiencies, and aeration tank organic loading rates are two of the prominent ones. Manipulation of the organic loading rate applied to the aeration tank and the BOD to nitrogen ratio (BOD/N) of the substrate were used in this study to promote changes in the microbial populations. The following combinations of F/M and BOD/N were used: $F/M = 0.5$, $BOD/N = 40$; $F/M = 1$, $BOD/N = 25$; $F/M = 0.5$, $BOD/N = 10$; and $F/M = 0.25$, $BOD/N = 20$. It should be pointed out that in this study F/M was defined as the weight of BOD_5 applied per unit weight of MLSS per day. The BOD/N is defined as the ratio of the weights of BOD_5 and nitrogen in the substrate. Based upon the data in the literature which were cited in the previous chapter the first combination created a nitrogen deficient condition, the second a marginal condition and the third and fourth combinations resulted in conditions where nitrogen was in excess or adequate. When the loading conditions were changed, about one-half of the contents of the aeration tank was wasted, the tank was refilled with dilution water and reseeded by feeding domestic sewage primary effluent for a short period of time.

B. Batch Flotation Tests

The equipment and procedure used in performing the batch flotation tests in this study were different in some respects than those which have commonly been used by other researchers. A diagram of the apparatus used in this study is given in Figure 3. The apparatus consisted of a saturation cylinder, a sludge discharge cylinder, two flowmeters, a source of compressed air, a plexiglass flotation cylinder and the necessary rubber tubing and fittings.

1. General Procedure

The tests were performed by saturating tap water or effluent from the continuous flow laboratory unit with air at pressures of from 40 to 120 psig in the saturation cylinder, passing the liquid through a pressure reducing valve, blending the air laden water with the sludge to be floated and introducing this blended material into the bottom of the flotation cell.

For the experiments requiring volumes of recycle water of 2200 ml or less, the saturation of the water with air was accomplished by placing a given amount of liquid in the saturation tank, and bubbling air through the liquid by means of a diffuser stone located near the bottom of the saturation tank. The pressure in the tank and the desired air flow rate were maintained by manipulating the pressure regulator on the air supply and by adjusting the purge valve located on top of the tank in order to permit continuous venting of air from the tank at the required rate. The air flow into the cylinder was measured by a flowmeter. The time of saturation was 5 min.

While the recycle water was being saturated, the sludge to be floated was placed in a graduated plexiglass cylinder from which it would

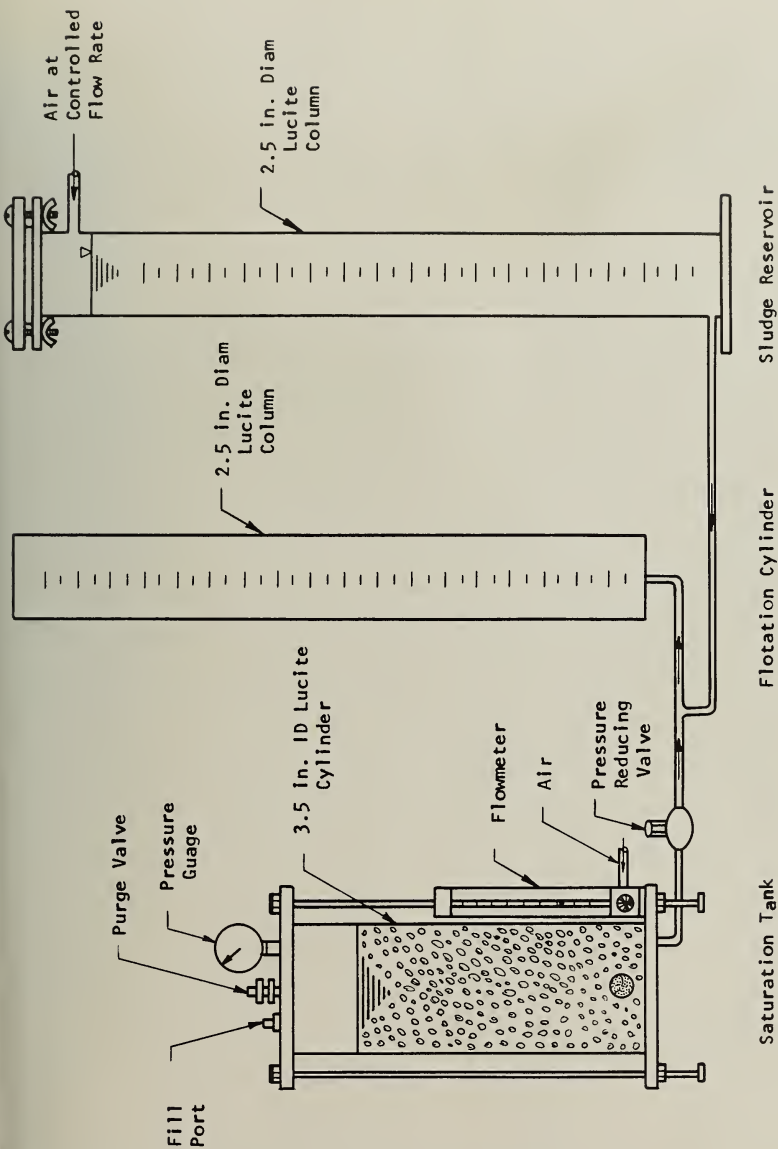


FIGURE 3. SCHEMATIC DIAGRAM OF THE BATCH FLOTATION TEST APPARATUS

be later forced at a controlled rate by air. The sludge was usually placed in the cylinder about one minute before the flotation test was to begin. In instances where it was placed in the cylinder earlier and any settling was noticed, the solids were redistributed by inverting the cylinder 3 or 4 times.

After saturation, the water was released at a constant rate through a pressure reducing valve^{*} and was blended in a 0.375 in. diam rubber tubing with the sludge to be floated. The sludge was simultaneously forced from the graduated plexiglass container by a flow of air which was controlled by means of a flowmeter. The blended material was discharged vertically through the bottom of a plexiglass column. Columns having nominal diameters of 0.625, 1.5, 2.5, 3.5 and 7.5 in. were used in various batch experiments which will be explained later. Columns were filled to a depth of 20 in. The volume of water left in the saturation tank and the volume of sludge remaining in the sludge cylinder after the flotation tube had been filled were used to verify the ratio of the volumes of water and sludge blended. The approximate solids concentration of the mixture in the flotation column before flotation was calculated. The level of the sludge-water interface was recorded at different time intervals as the sludge rose toward the top of the column. The rate at which the interface ascended was recorded as the interfacial rise rate. Typical curves illustrating the course of the rising of the interface with time are shown in Figure 4.

For tests which required volumes of recycle water greater than 2,200 ml the water was saturated in a different manner. The liquid to be

* No. 431 V-stem, bellows valve or a No. 411 1M 2B V-stem bellows valve, manufactured by Hoke Inc., Cresskill, New Jersey.

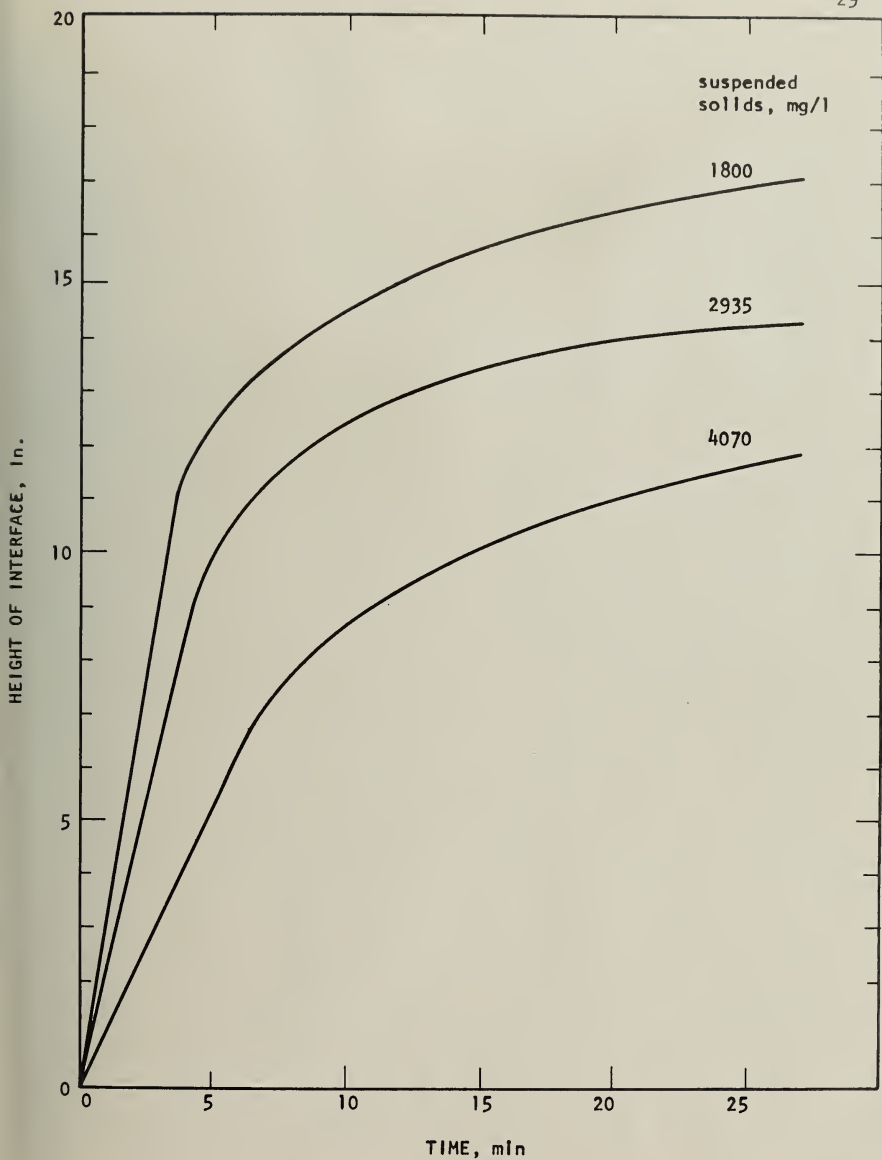


FIGURE 4. TYPICAL BATCH FLOTATION CURVES

saturated was placed in a steel tank having a capacity of 10 liters. The tank was sealed and compressed air at the desired pressure was applied to the tank. The tank was placed on a gyratory shaker^{*} and shaken for 20 min at a rate of 130 rpm. The water treated using this method usually was saturated to a lesser degree than that saturated by the method described previously. Since the experimental work was carried out using gas release data rather than degree of saturation data, the fact that the two methods of saturation did not give the same degrees of saturation was of little importance.

2. Standard Batch Flotation Test Procedure

The standard flotation test described in this section was used to compare the floatability of the various sludges with their rheological properties. These tests were performed using the general procedure described above. Recycle water saturation was accomplished by bubbling air through 1,600 ml of water at 40 psig pressure at a rate of about 7.28 l/min for 5 min. The sludge and recycle water were blended and discharged through the bottom of a 2.5 in. diam plexiglass tube. The interfacial rise rate curve was plotted using data collected as the sludge rose in the column. Twenty min after the columns were filled, duplicate samples for determining the concentration of solids in the float were withdrawn from the top 0.25 in. of the float layer with the aid of a rubber bulb and a short length of glass tubing. The samples were stored in tared, capped, glass weighing bottles until they could be weighed. The samples were weighed, dried overnight at 103°C, cooled and reweighed. The concentration of solids in the float as calculated from these data was expressed as percent

* Model G-10 gyratory shaker manufactured by New Brunswick Scientific Company, New Brunswick, New Jersey

solids in the float. The time of sampling, 20 min, was arbitrarily selected.

3. Comparison of Methods for Performing Batch Flotation Tests

As stated earlier, the method of carrying out the batch flotation tests in this study differed somewhat from the method more commonly used (Eckenfelder et al., 1956) (Hurwitz and Katz, 1959). With the practice which has commonly been used in batch testing the liquid to be saturated is placed in a pressure vessel, the air above the liquid is pressurized to the desired pressure of saturation, and then the liquid is saturated by manually or mechanically shaking the pressurized vessel for some predetermined length of time. The sludge to be floated is placed in a one liter cylinder which serves as the flotation tube. While maintaining the pressure in the vessel, the air laden water is discharged through the pressure reducing valve and by means of a length of laboratory tubing is conveyed to the one liter cylinder where it is mixed with the sludge. When the cylinder is filled to the level required, the recycle water tube is removed and observations of the interface height are made as the flotation progresses with time.

The method used in this study differs from the common method in two ways: (1) the saturation of the water was accomplished by the continuous bubbling of air through the water rather than by shaking and (2) the blending of the sludge and the air laden water was done outside the flotation tube by combining the proportioned flows of sludge and aerated water prior to their discharge into the flotation tube.

In order to determine whether any appreciable difference in rise rate resulted from the use of the two different methods of blending, a

test was conducted in which aliquots of a filamentously bulked activated sludge were floated using each scheme. Water was saturated by bubbling air through it for both tests. A portion of activated sludge was placed in a one liter cylinder and aerated water was blended with it in the cylinder until the 15 in. level was reached. A second cylinder was filled to the 15 in. level using a tube following the blending of sludge and air laden water in the tube. The concentration of suspended solids in both cylinders was essentially the same. The data necessary for determining the rise rates were recorded.

The appearance of the contents of the two cylinders differed considerably as flotation progressed. The sludge which had been blended in the cylinder did not appear to have nearly as well a defined interface as did the one which had been blended with the air-laden water prior to being introduced into the cylinder. The former seemed to have quantities of somewhat loose, diffuse, clumps of sludge which remained below as the remainder floated toward the top. The sludge which was blended before being introduced into the column, however, had a much more homogeneous appearance immediately after the tube had been filled and seemed to maintain this as flotation proceeded. The average rise rates recorded on aliquots of the same sludge were 207 and 400 ft/day, respectively, for the tests using the common and the in-line methods of blending.

In order to determine whether the difference in rise rates resulting from the different methods of blending would prevail for other sludges, a similar experiment was performed at a later date using a less severely bulked sludge. These experiments which were carried out using one liter cylinders gave average rise rates of 326 and 338 ft/day, respectively, for the sludges floated using the common method and the in-line

method of blending. These results compared much more favorably as the difference between the rise rates here are within the range of experimental error.

From these tests made using a bulked activated sludge it appears that in-line blending gives a more homogeneous material in the flotation cell at the beginning of flotation with the result that higher rise rates and more complete flotation of the solids occurs. These improvements are believed to result from more even distribution of air among the solids due to the continuous proportioning and intimate contact which takes place during the in-line blending process. The magnitude in the differences in the rise rates obtained using the two methods of blending appear to change as the sludge characteristics change.

4. Reproducibility of Batch Flotation Data

The reproducibility of batch flotation results was evaluated by making 10 replicate determinations on a sludge of essentially the same concentration. The tests were made using a recycle ratio of 0.77, at 40 psig and a stock sludge concentration which gave a final suspended solids concentration in the flotation tube of 2,165 mg/l when the contents of the tube were uniformly mixed. The results of the series are given in Table 2.

TABLE 2
REPRODUCIBILITY OF BATCH FLOTATION DATA

Measurement	No. Det.	Mean	Std. Dev.	Coef. of Variation
Rise Rate	10	225 ft/day	16.8 ft/day	7.47%
Float Conc.	10	1.42%	0.061%	4.3%

These data show that there is considerable variation in the results of batch flotation tests, especially in the rise rate determination. Considering the factors involved in the performance of the tests, these variations are not felt to be excessive. The data indicated the need for making multiple flotation tests. Consequently all batch flotation tests performed for the purpose of comparing rise rate and float solids concentrations data with other properties of the sludge were made in triplicate.

5. Effect of Column Filling Time on Interface Rise Rate

The problem of attaining a uniform distribution of solids in an experimental flotation column is one which must be considered in the performance of laboratory flotation tests. The distribution of the solids in the column is influenced by the rate and manner in which the column is filled. The result of filling a column too slowly may be the redistribution of the solids in the column as they start to float even before the filling of the column has been completed. In extreme cases this might be evidenced by the formation of an interface between rising sludge and the clarified underflow even before the column is completely filled. On the other hand, it is undesirable to fill the column so rapidly that the turbulence created will break up the floc to the point that a long lag time for reflocculation is required before interface formation is seen.

Dick (1965) in his studies on the thickening of activated sludge by gravity sedimentation explored in detail the problem of attaining uniform solids distribution in 3.5 in. diam laboratory settling columns. The method he developed for minimizing the uneven distribution of solids involved filling the column from the bottom by pumping sludge at a rate which was rapid enough to prevent sedimentation from commencing during

filling. The filling time also was slow enough to prevent the turbulence from being so great that redistribution would take place during the lag period between the end of the filling procedure and the time when sedimentation at a constant velocity began. Farnsworth (1967) also investigated the effect of column filling time upon settling velocity. The plot showing the relationship between filling time and settling velocity passed through a range of minimum settling velocities. The filling time chosen as giving the most nearly uniform solids distribution also gave a settling velocity which plotted near the minimum value.

The column filling times chosen for use in this study were those which in a series of tests using various filling times gave the lowest rise rates. The determinations of the column fill times to be used here were made in the following way. Sludge was taken from the continuous activated sludge system in sufficient quantity to complete a series of tests using a column of a particular diameter. The recycle water from the saturation system of the continuous flotation unit was used as the recycle water for the batch tests with the columns. With this exception a system very similar to the one described earlier for performing batch flotation tests was used. Sludge was displaced from a 13 liter carboy at a controlled rate by air. The sludge was blended with recycle water and discharged into a flotation column vertically through the bottom. The flow rate of the recycle water was controlled by maintaining a constant differential head on a manometer which was connected across an orifice on a line from the discharge side of the continuous unit saturation system. The times of filling of the columns were varied by continuously bleeding off some of the blended sludge as the column was being filled. The time required to fill a column was thus controlled by the fraction of the feed

which was bled off. In any given series of tests made on a particular column size the air to solids ratio was held constant.

In order to decrease the turbulence in the columns during filling at the rapid rates required, it was necessary to feed the sludge into the larger columns through more than one tube. Two 0.5 in. diam tubes were used to feed the 7.5 in. diam column. All tests were made with the columns being filled to a height of 20 in.

The data showing the effect of column fill time on interfacial rise rate are plotted in Figure 5. Based upon these data it was decided that a fill time of one minute or less for the 2.5 in. diam and 3.5 in. diam columns and of about 3 minutes for the 7.5 in. diam column would give reliable results and would be used in future tests. Fill times of less than one minute were used for the 0.625 in. diam and 1.5 in. diam tubes. It was noted during the course of the ensuing experiments that when the columns were filled at these rates considerable turbulence was evident during the filling process. For the higher concentrations of sludge the turbulence seemed to be confined primarily to the bottom one third of the column during filling while the sludge above seemed to rise as a unit with the filling of the column. For the lower sludge concentrations there was considerable turbulence throughout the column during and for some time after the column had been filled.

6. Effect of Column Diameter on Rise Rate

The importance of considering the effect of column diameter upon settling velocity when making batch laboratory sedimentation tests has been pointed out by recent investigators studying the thickening of activated sludges by gravity sedimentation (Vesilind, 1968; Cole, 1969).

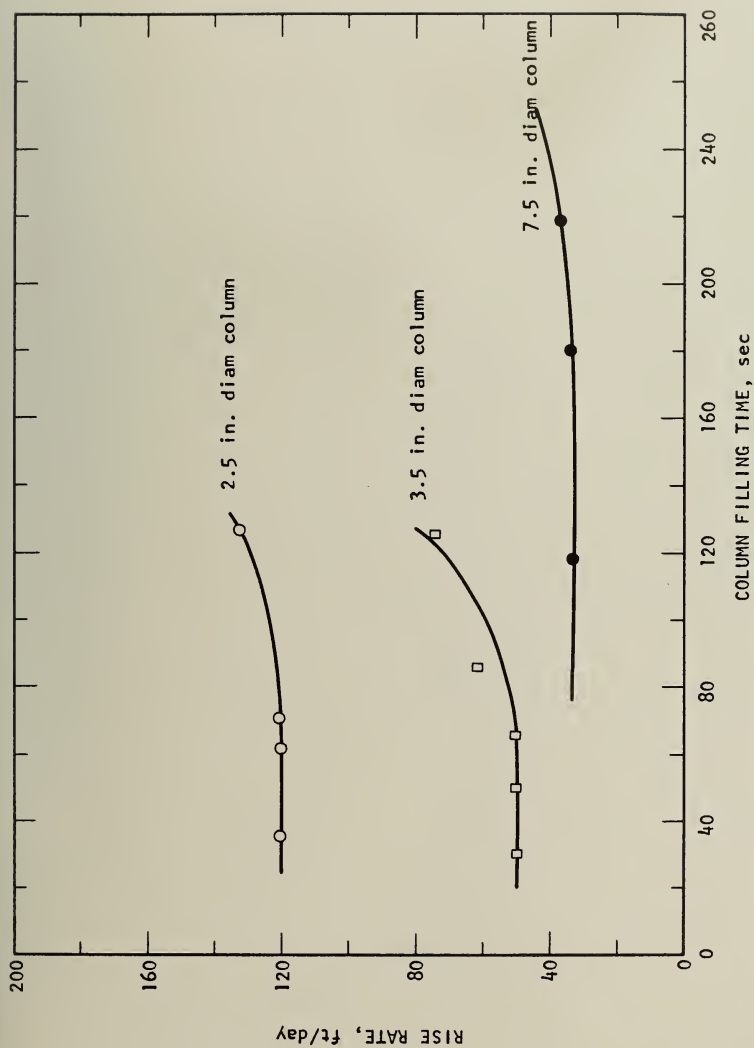


FIGURE 5. EFFECT OF COLUMN FILLING TIME ON RISE RATE

Earlier workers in the same or similar areas of interest had determined that column diameters of about 2 in. were suitable for performing settling tests and that larger columns had no beneficial effect (Mancini, 1962) (Kammermeyer, 1941). Vesilind (1968) in his work with activated sludges investigated the effects of column diameter on settling rates using columns having nominal diameters of 4, 8, 18, and 36 in. The sludge concentrations studied ranged from 2,000 to 10,000 mg/l. Figure 6 is taken from his data and shows the influence of column diameter on settling rates over a range of solids concentrations. At low concentrations two different mechanisms were used to explain the behavior of the sludge in the small diameter columns. The first is the phenomenon of bridging. At high solids concentrations the floc particles of the sludge interact to form a bridging structure across the column resulting in slower settling rates than are attained at the same concentration in larger columns. The other mechanism which probably operates at all sludge concentrations results in faster settling rates in small columns than would be experienced in larger columns containing sludge at the same concentration. In this case water being squeezed out as the sludge compresses takes the path of least resistance and flows along the smooth wall of the column rather than going by the more tortuous route through the pores of the sludge mass.

One other phenomenon of batch settling tests which is related to column diameter concerns the agglomeration of sludge floc into clumps and the effect of this agglomeration upon settling rates. The agglomeration or clumping together of sludge floc provides channels and larger pore spaces for the passage of escaping water thus permitting faster settling rates. Vesilind (1968) studied the incidence of agglomeration in columns of several diameters and found that in order to get reproducible laboratory

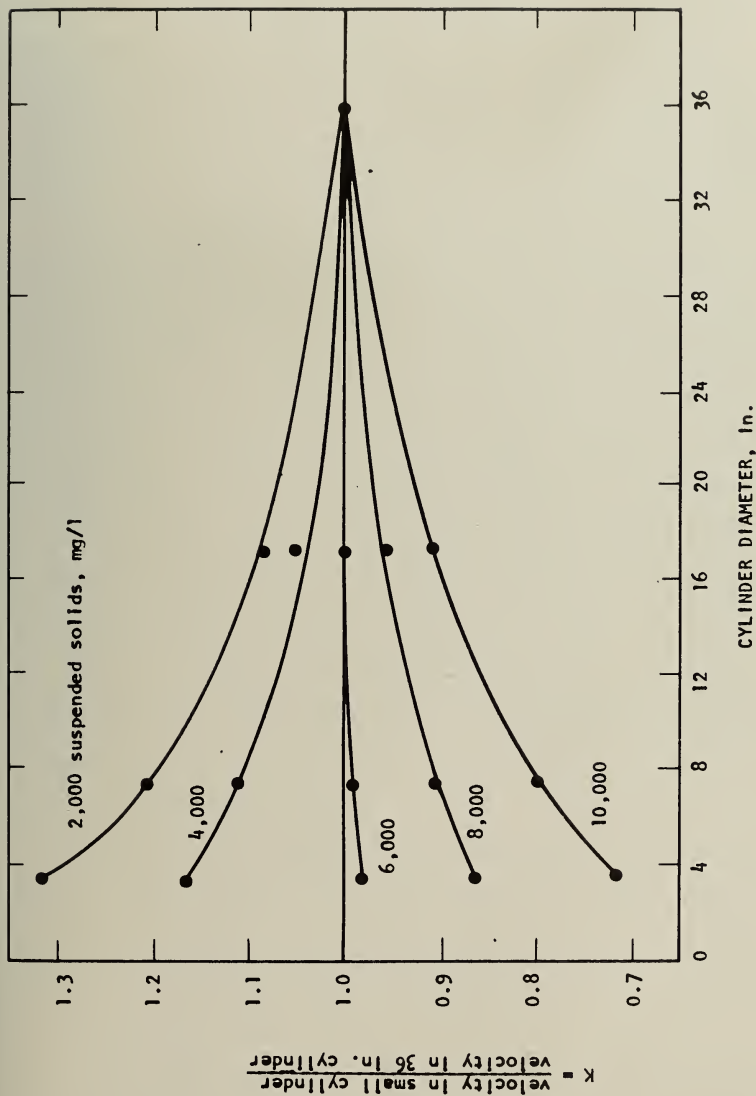


FIGURE 6. EFFECT OF CYLINDER DIAMETER ON INTERFACE VELOCITY (From Vesilind 1968)

settling data consistently it was necessary that test conditions be controlled such that complete agglomeration would take place in all tests. He found agglomeration to be enhanced by low solids concentrations, larger column diameters, and long filling times. Incomplete agglomeration or lack of agglomeration, then, is more likely to occur in tests performed using small diameter columns and sludges having high solids concentrations.

Since the flotation process is essentially sedimentation in reverse, it seemed advisable to investigate the effect of column diameter upon the rise rates obtained from batch flotation tests. This was done using columns of 1.5, 2.5, 3.5 and 7.5 in. diam and the sludge blending procedure described in the previous section. The columns were filled to the 20 in. level in all tests as previously stated. The data obtained from several series of tests are presented in Figure 7. It should be pointed out that these data were collected on different dates and not necessarily at the same air to solids ratios. Therefore, the data of one series of tests should not be compared directly with those of another series. The air to solids ratio was held constant for all tests made in any particular series. Thus, comparisons can be made between rise rates in columns of various sizes in a given series of tests but not between columns in different series of tests.

These data plot reasonably well as straight lines on log paper. This is in general agreement with the data of Vesilind (1968). From this plot it may be possible by extrapolation to obtain rise rate data for columns of other diameters. The data shown here indicate that decreasing column diameters gave higher rise rates for the dilute sludges. For sludges in the 5,000 to 8,000 mg/l range, column diameter did not have much influence on rise rate. An important point to note, however, is that on

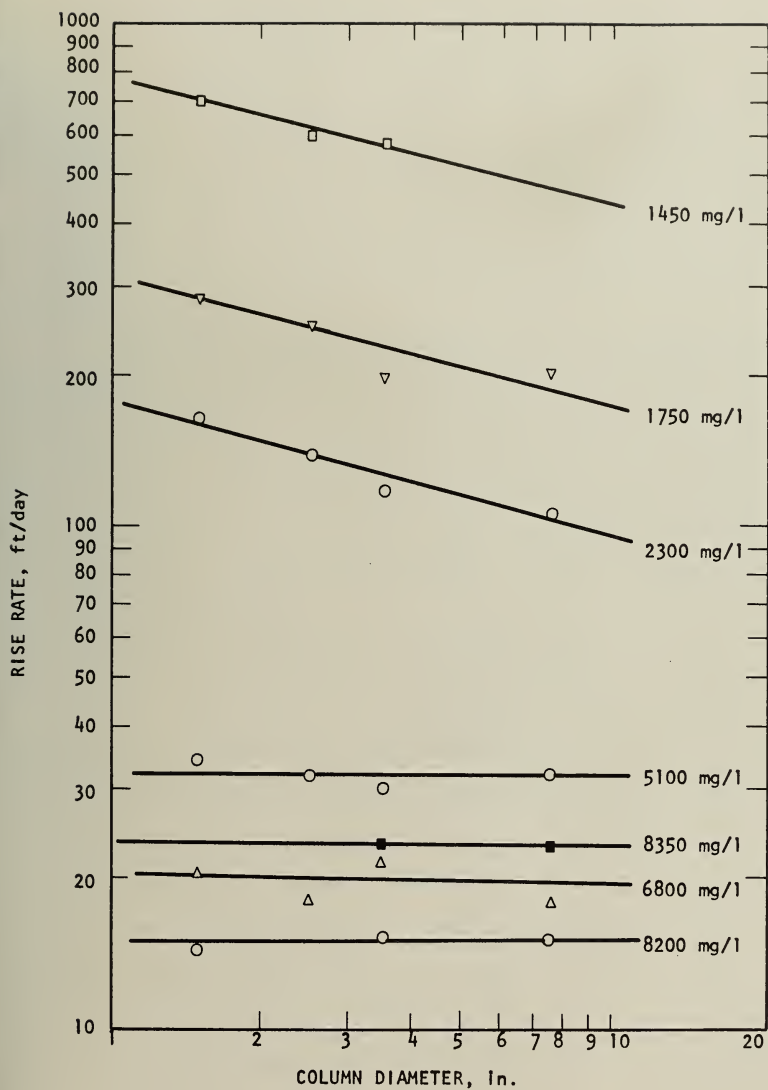


FIGURE 7. EFFECT OF COLUMN DIAMETER ON RISE RATE

two occasions while substantial rise rates were being recorded for the 7.5 and 3.5 in. diam columns, the sludges in the 2.5 and 1.5 in. diam columns exhibited virtually no rise rate at all. This was probably due to bridging and to lack of agglomeration which was discussed previously.

It should be pointed out that the results obtained were dependent upon the sludge characteristics and would be expected to vary from sludge to sludge.

Based upon these data it is apparent that in performing batch flotation tests one should consider the effect of column diameter upon rise rate. Column sizes as large as practicable should be used to minimize the possibility of bridging and to encourage agglomeration of the sludge in the column. In this study, columns of 3.5 and 7.5 in. diam were used. The 7.5 in. diam column was used only for tests made using high sludge concentrations.

7. Effect of Column Depth on Initial Rise Rate

Until recent years the procedures used in the design of gravity thickeners have not taken into account the effect of the depth of sludge upon the subsidence rate of sludges in laboratory batch test columns. The Kynch theory which was developed for and has been proven to be correct for ideal suspensions had been used with modifications in the design of thickeners for thickening activated sludge, a flocculent material. A few investigators had considered the effect of depth on settling rate. Gaudin, Fuerstenau and Mitchell (1962) found that for concentrated Kaolin suspensions depth influenced the settling velocity but at dilute concentrations the velocity was practically independent of depth. Clifford and Windridge (1932) found that the settling velocity of activated sludge was directly proportional to depth, but their work was limited to depths of

less than 1 ft.

Taking issue with the prevailing concept that the initial settling rate of a suspension was a function only of the solids concentration, Dick (1965) investigated the effect of initial sludge depth on the subsidence rate of activated sludges in laboratory batch test columns. His experiments with activated sludge showed that the subsidence rate is greatly influenced by sludge depth. By arranging his data such that the initial depth divided by initial settling rate was plotted against the initial depth he obtained lines which could be described by an equation of the following form:

$$\frac{D_o}{V_o} = R + S D_o \quad (2)$$

where

D_o = initial depth of sludge

V_o = initial subsidence rate

S = slope of the plot

$R = \frac{D_o}{V_o}$ at $D_o = 0$

The magnitude of the value of R is a measure of the extent of retardation of settling and hence was called the retardation factor. The retardation factor was interpreted as being a measure of the support which the sludge interface received from the underlying layers of sludge. He found that the retardation factor was dependent upon the solids concentration and the nature of the sludge. Vesilind (1968) found the retardation factor also to be dependent upon the diameter of the column in which the tests are performed.

To the author's knowledge, the effect of sludge depth upon rise rates in batch flotation tests has never been investigated. In order to

determine whether or not the depth of the sludge in a flotation column had any effect upon the interfacial rise rate, a series of experiments were performed using laboratory developed sludges and the same batch flotation procedure described previously in the section dealing with the influence of column fill time on rise rates. Experiments were performed using three sludge depths under each set of conditions. For any given series of tests using three depths, the air to solids ratio and the suspended solids concentration were held constant. The air to solids ratios for different series of tests, however, were not necessarily the same. The data for these tests are plotted in Figure 8. These plots show that the interfacial rise rate is directly proportional to the initial depth of sludge in the column at least for depths between 1.5 ft and 4 ft. The effects of depth are seen to be greater at high sludge concentrations. When the data are plotted with D_0/V_0 on one axis against D_0 on the other the data plot as straight lines fitting the equation developed by Dick (1965). Thus, a retardation factor exists in flotation as well as in gravity sedimentation. The data for several sludges are plotted in Figure 9.

The sludge in gravity sedimentation which provides the structural support for the overlying layers is believed to derive its support from physically contacting the bottom of the column. With flotation there is no fixed surface against which the most concentrated sludge layer can bear for support. The supporting force here may be developed by the weight of that amount of sludge in the topmost layers of float which are lifted above the original liquid level in the column and by the friction of the sludge against the column wall.

8. Effect of Pressure of Saturation on Batch Test Rise Rates

In order to obtain batch flotation data at high blended sludge concentrations, recycle water saturated at pressures up to 120 psig were

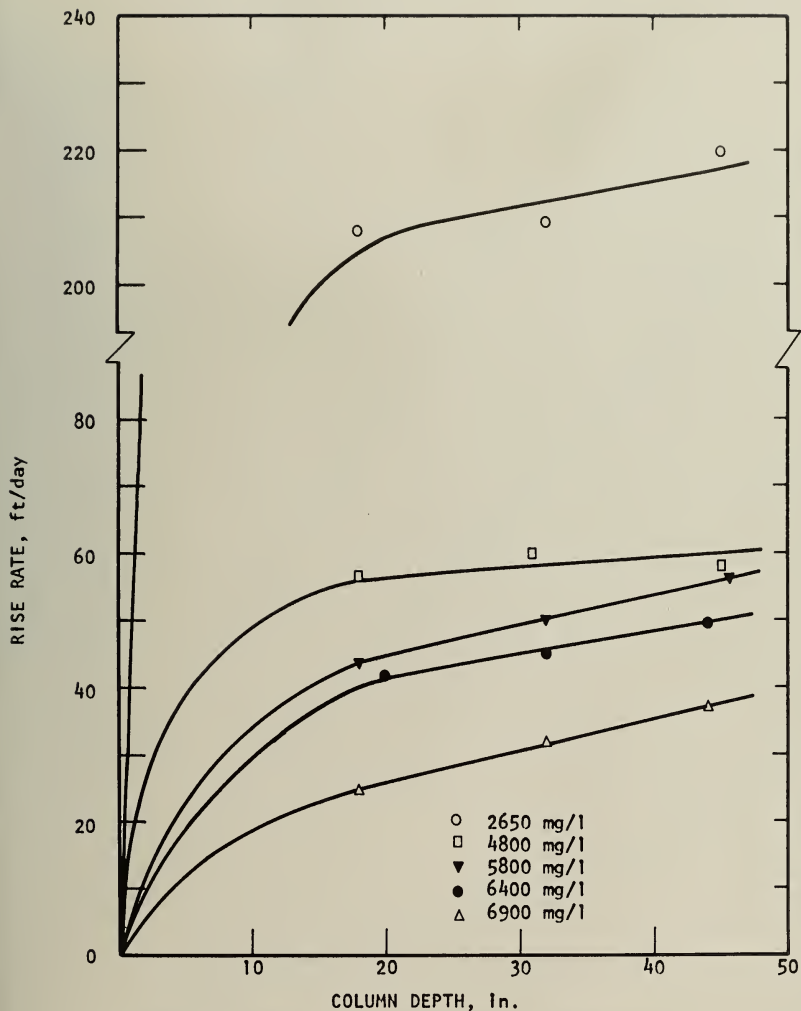


FIGURE 8. EFFECT OF COLUMN DEPTH ON RISE RATE

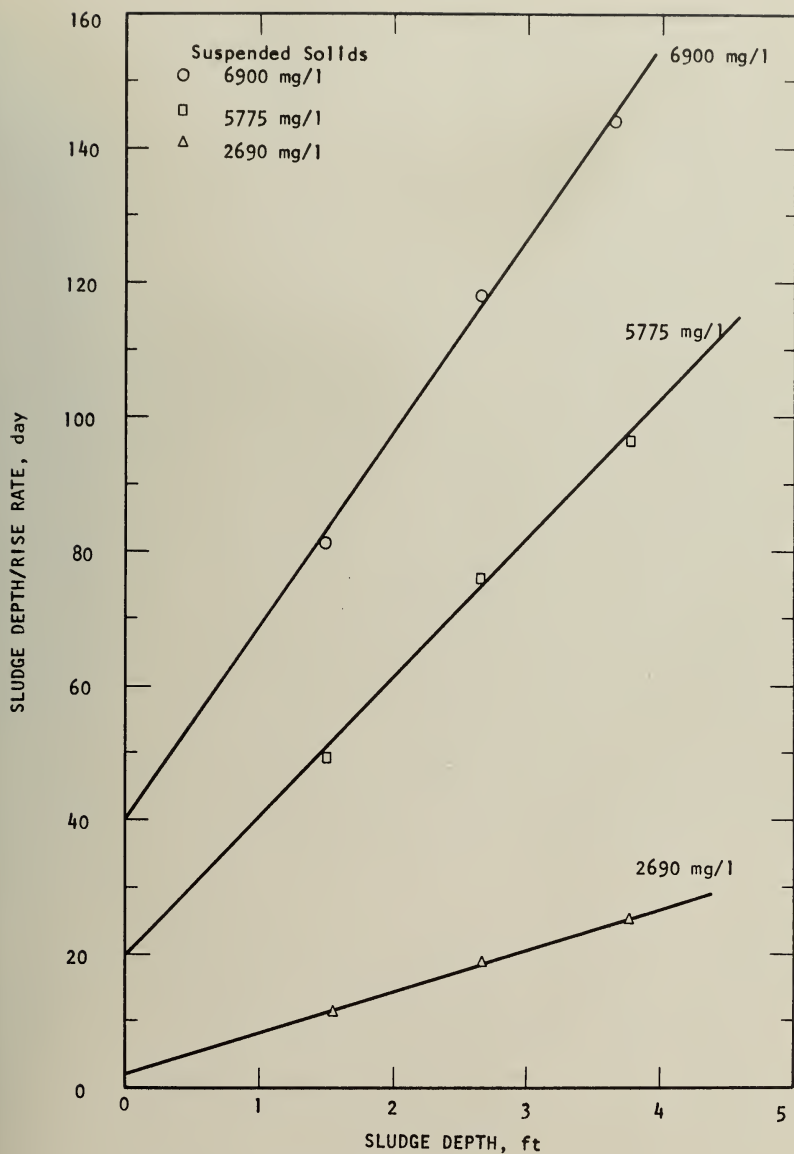


FIGURE 9. DETERMINATION OF RETARDATION FACTOR

used in order to provide the air necessary to maintain a constant air to solids ratio. The air release data were measured for pressures of 40, 60, 80, and 120 psig. Two series of tests were performed using recycle water which had been saturated at 40, 60, and 80 psig to determine if the changing of the pressure had any influence on the rise rate. The data obtained for the two series of tests are shown in Figure 10. From this figure it can be seen that even though the air to solids ratio and blended sludge concentration were held constant in each series the rise rates decreased exponentially as the pressure increased. This may have been due to the increased probability of bubble agglomeration at the higher pressures. Katz (1963) reported that the number of air bubbles produced upon depressurization will be directly proportional to the product of the absolute pressure and the rate of flow of the pressurized air charged stream. He also stated that increasing the pressure substantially over 80 psig may not result in an increased production of useful bubbles because of the increasing rate of bubble agglomeration. Theoretically, the number of air bubbles necessary to achieve satisfactory flotation is proportional to the number of particles to be floated. The discharge of bubbles having diameters of a millimeter or more was noted here when a saturation pressure of 120 psig was used.

Ettelt (1964) has stated that smaller bubbles have less liquid to displace from the surface of the solids to which they must attach and; therefore, they attach more readily than larger bubbles. Additionally, because their terminal velocities are less than those of larger bubbles, the detention time is also increased, which appreciably enhances the opportunity for contact with the solids.

Vrablik (1958) reported the bubble size distributions he

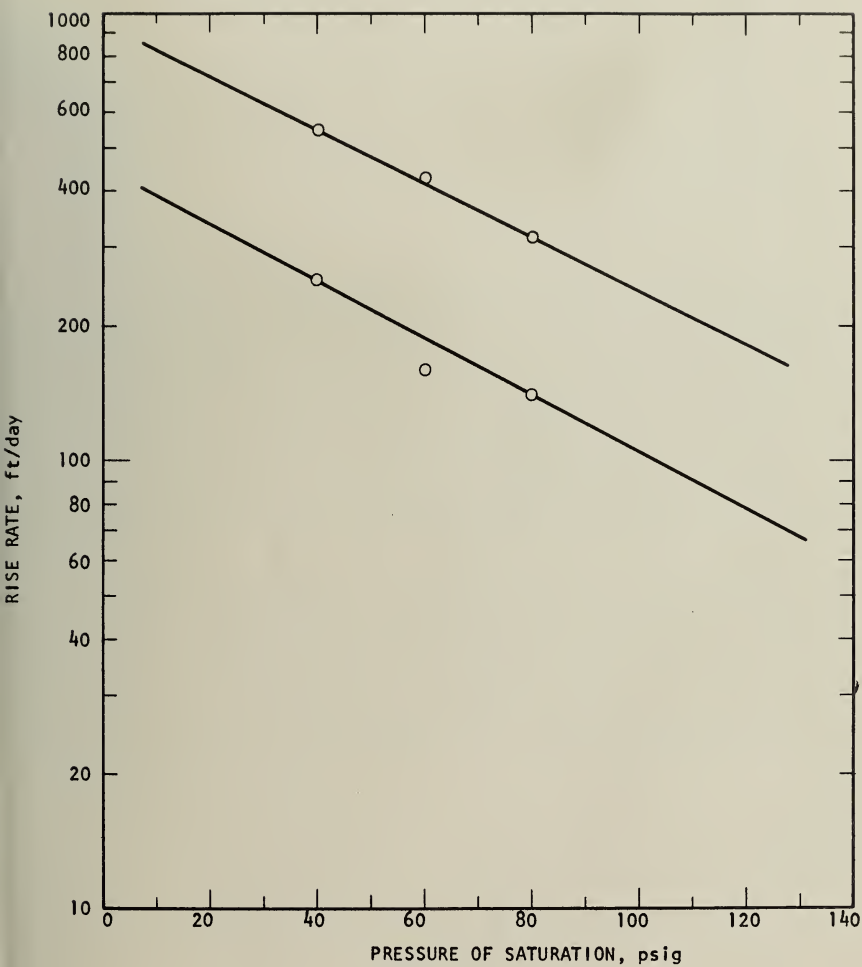


FIGURE 10. EFFECT OF PRESSURE OF SATURATION ON RISE RATE

obtained from depressurizing water which had been saturated at pressures of 20 to 50 psig. His data showed that the range of bubble sizes were identical for the two pressures but that the higher pressure gave a more uniform distribution of sizes. Both pressures gave modal values in the 70 to 90 micron diam range. Data for higher pressures were unfortunately not available.

9. Summary

A number of factors which influence the results obtained from batch flotation tests have been pointed out in the preceeding discussion. The data presented showed that column diameter, the column filling time and column depth, and pressure of saturation do affect the interfacial rise rate. The magnitude of the effects of column diameter and column height would be expected to vary depending upon the characteristics of the sludge.

A test procedure for performing the batch flotation tests was described. This method which included blending of the sludge and recycle water prior to their discharge into the flotation column was found to give higher rise rates than the more commonly used procedure, especially with the more filamentous sludges.

Nowhere in the literature was anything found to indicate that the factors mentioned previously have been considered in the performance of the batch flotation tests or in the use of the data obtained from them. That the results obtained from prototype flotation units do not always agree with the results predicted from the data obtained from batch flotation tests has, however, been reported (Ettelt, 1964; Katz, 1968; Shell, 1970; and Horne et al., 1962). Generally the prototype units give higher float concentrations than are obtained in the batch flotation tests, but not

always.

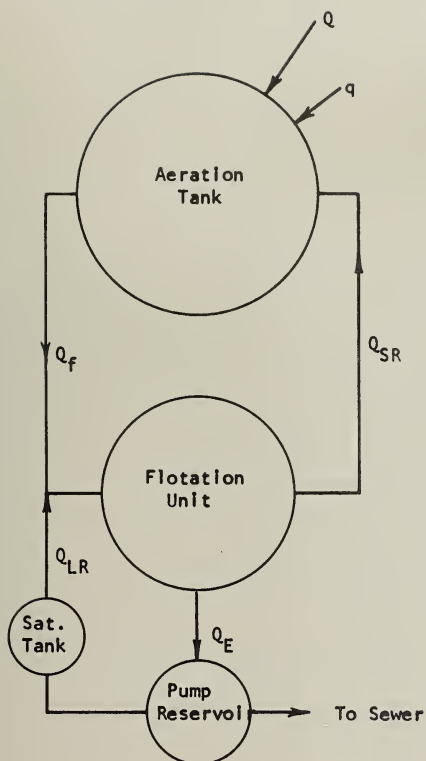
The dynamic and hydraulic factors existing in a continuous full scale unit undoubtedly influence the results obtained. On the other hand, it is suggested that consideration of the factors pointed out earlier which affect the batch flotation test may give data which more nearly approximate the results which may be obtained from a full scale unit.

C. Solids Flux Analysis

1. Procedure for Obtaining Data from Continuous Laboratory Flotation Unit

The object of this portion of the study was to investigate the possibility of using the solids flux method of analysis to predict the operation of continuous flotation units. With the continuous system operating at assumed steady state conditons the following operational data were needed in order to make comparisons between it and the batch flux curve: (1) the solids loading to the flotation unit, (2) the volumetric and mass rates of sludge withdrawal from the flotation unit and (3) the air to solids ratio being used. The methods used to obtain these data will be explained with the aid of the schematic diagram of the continuous flow system as shown in Figure 11. Steady state conditions in the flotation unit were assumed to exist after the unit had operated under a given set of conditions for a period of at least 3 hrs.

With the MLSS having been determined, the hydraulic flow rate, Q_f , to the flotation unit is the only additional information needed to determine the flux being applied to the flotation unit. This information was ascertained by measuring the dilution water flow rate, Q ; the substrate feed rate, q ; and the sludge recycle rate, Q_{SR} . The float skimmers



- Q = Dilution Water Flow Rate
- q = Substrate Flow Rate
- Q_F = Aeration Tank Discharge Flow Rate
- Q_{SR} = Sludge Recycle Flow Rate
- Q_{LR} = Liquid Recycle Flow Rate
- Q_E = Flotation Unit Effluent Flow Rate

FIGURE 11. SCHEMATIC FLOW DIAGRAM OF THE CONTINUOUS FLOW LABORATORY ACTIVATED SLUDGE SYSTEM

discharged their sludge to a small pump reservoir where it was collected until it made up about 3 to 4 liters and then it was pumped back to the aeration tank. The time interval between pumping, depending upon the operational conditions, ranged from 2 to 6 min. The measured amount of sludge returned at a pumping was divided by the pumping interval to give the average sludge recycle rate. The sum of the flow rates of the dilution water, the substrate and the sludge recycle gave the flow rate to the flotation tank. The product of the weight of the MLSS per unit volume of mixed liquor and the hydraulic flow rate divided by the area of the flotation zone was the applied flux. The solids concentration of the float was determined in the following manner. The float returned to the aeration tank during a single pumping cycle was collected and mixed thoroughly. A 50 ml aliquot was withdrawn and diluted 1:5 or 1:10. Duplicate 10 ml samples were processed according to the procedure used for MLSS determinations.

The liquid recycle rate and the gas release rate had to be determined so that the air to solids ratio could be calculated. Since the flowmeter on the recycle line was not sufficiently accurate, the liquid recycle rate was determined by measuring the rate of effluent discharge from the flotation unit, Q_E , and running a flow rate balance on the flotation unit. The air released from the recycle water was measured as described in the following section. An example of a typical calculation is given in the Appendix.

2. Procedure for Determining Quantity of Air Released

The air to solids ratio is an important parameter in flotation. In order to match the air to solids ratios of the batch tests to those of the continuous unit, it was necessary to determine the amount of air

released from the recycle water upon depressurization for each system at the particular operating conditions employed. A method somewhat similar to the one used by Vrablik (1958) was employed to make these measurements. The following procedure was used.

Two graduated 2-liter gas sampling tubes clamped vertically to a ring stand were connected at the top with a short length of laboratory tubing as shown in Figure 12. A manometer using colored water as an indicating liquid was positioned such that it could be connected to the tubing joining the two sampling tubes. The bottom end of one of the sampling tubes was connected by a short length of tubing to the discharge side of the pressure reducing valve of the water saturation system. Prior to beginning a test the body of tube 1 was empty and the water level was adjusted to level A in the lower tubing connection. The manometer was not connected at this time. Tube 2 was filled through the bottom with dibutyl phthalate to a level of about 1.5 liters. One leg of the manometer was then connected to the tubing joining the two sampling tubes. The pressure reducing valve was opened to permit air laden water to discharge to tube 1. Simultaneously, dibutyl phthalate was drained from tube 2 at a rate sufficient to prevent the loss of manometer fluid and yet slow enough so that a slight positive pressure was maintained on the side of the manometer connected to the apparatus. When about a liter of water had been discharged into tube 1 the pressure reducing valve was closed and enough dibutyl phthalate was withdrawn to bring the liquid level in the manometer back to its original level. A minute or two was allowed to make the final adjustment. Once the final adjustment was made the manometer was disconnected and water was drained from tube 1 until the water level returned to point A. The volumes of water and dibutyl phthalate withdrawn were

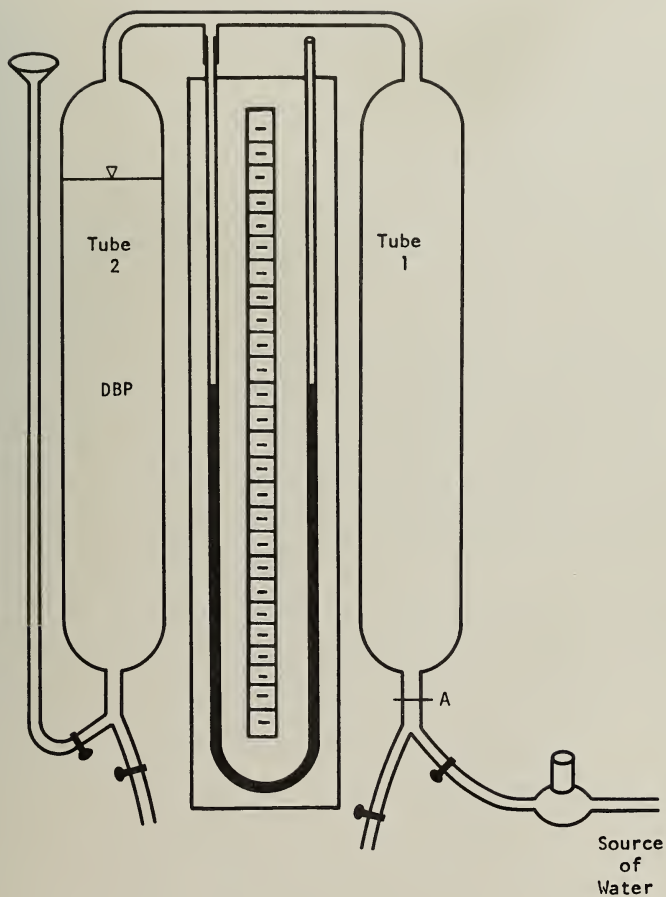


FIGURE 12. APPARATUS USED TO MEASURE VOLUME OF GAS RELEASED FROM WATER UPON DEPRESSURIZATION

measured and the difference between these two volumes represented the volume of gas released in passage through the pressure reducing valve. The volumes measured were corrected to standard conditions.

With the batch saturation tank, the gas sampling tube was connected to the pressure reducing valve by means of a short length of hose. For the laboratory continuous unit the hose was connected to a valve which was identical to the pressure reducing valve but which had been installed in a tee on the upstream side of the pressure reducing valve which served the continuous unit.

Data collected from the batch saturation tank indicated that for the 40 psig and 80 psig pressures of saturation about 92 percent and 96 percent, respectively, of the amount of air which could theoretically be released from solution upon depressurization, was released. The extent to which the valve was opened did not make a significant difference in the volume of gas released from solution.

For the continuous flotation unit, when operating at 48 to 50 psig, about 70 percent of the amount of air which could theoretically be released upon depressurization was released.

3. Procedure for Obtaining Data for Batch Flux Curves

The batch flux curves were drawn from calculations based upon the data collected from a number of rise rate tests made using laboratory columns containing blended sludges at various solids concentrations. The air to solids ratio, which determines the driving force, was kept constant for all tests relating to a particular flux curve. This was accomplished by utilizing, for successive tests, recycle water which had been saturated at different pressures and by employing stock sludges of different concentrations. The air release data for the various pressures of saturation

were obtained by the method described in the previous section. As a rule the tests requiring low concentrations of sludge in the flotation tube were made using recycle water which had been saturated at 40 psig. Subsequent tests, necessitating the use of higher concentrations, were made with more concentrated stock sludges and with recycle water that had been saturated at higher pressures.

The sludges used in these tests were obtained by collecting the float from the continuous unit and letting it sit quiescently and thicken further. After thickening, the sludge was sampled to determine the concentration and then held under aeration for the duration of the experiment. The more dilute stock sludges were made by diluting the concentrated stock with continuous unit effluent. The effluent from the continuous unit was saturated under pressure and used as the pressurized recycle water for the batch tests. In the case of the tests performed on the full scale flotation unit primary effluent was used as the recycle water. The full scale flotation unit also used primary effluent for recycle water.

The equipment needed to perform the tests was essentially the same as that described previously in the discussion of the batch flotation testing procedures. The columns used here were 3.5 in. in diam for the lower sludge concentrations and 7.5 in. diam for the highest concentrations. The large column was used in order to try to minimize the opportunity for bridging at high solids concentrations. For all tests performed using the 3.5 in. diam columns the small plexiglass saturation cylinder was used to saturate the pressurized recycle water. Because of its limited volume it could not be used in the tests performed using the 7.5 in. diam column. A steel tank of about 10 liters capacity was used to supply the recycle water when large volumes were needed.

The blending schedule for a flux curve was determined as follows.

The air to solids ratio of the continuous unit was determined. Since the batch tests had to be performed at the same air to solids ratio the batch and continuous air to solids ratios were equal and constant.

$$(A/S)_C = (A/S)_B = \frac{V_w V_g P_g}{V_s C_s} \quad (3)$$

where

$(A/S)_B$ = air to solids ratio for batch test, g gas/g solids

$(A/S)_C$ = air to solids ratio for continuous unit, g gas/g solids

V_w = volume of recycle water, l

V_s = volume of stock sludge, l

C_s = concentration of stock sludge, g/l

V_g = volume of gas released from recycle water saturated at stated pressure, l/l at STP

P_g = density of gas, g/l at STP

Then at any given pressure of saturation,

$$\frac{A/S}{V_g P_g} = K = \frac{V_w}{V_s C_s} \quad (4)$$

$$K C_s = \frac{V_w}{V_s} \quad (5)$$

Once the K value was determined for each pressure then it was only a matter of multiplying the stock sludge concentration and the K constant to determine the ratio of the volumes of dilution water to sludge which was necessary to maintain the constant air to solids ratio. The resulting solids concentration, C_m , in the flotation tube after blending is

given by the equation:

$$C_m = \frac{C_s}{1 + \frac{V_w}{V_s}} \quad (6)$$

If it was more desirable to select values of blended sludge concentration, the concentration of the stock sludge required to maintain constant A/S at a given pressure of saturation was found by the equation:

$$C_s = \frac{C_m}{1 - K C_m} \quad (7)$$

A typical blending schedule for an air to solids ratio of 0.0046 is shown in Table 3. The procedure used in this study was to select concentrations of stock sludge and by looking at the values of C_m in the blending schedule the most desirable V_w/V_s was selected. Because of the limited volumes of the saturation cylinder and stock sludge cylinder it was necessary to keep the ratio V_w/V_s between about 0.75 and 1.45. This necessitated the changing of pressures more often than otherwise would have been desired.

It should be pointed out that in this study, the A/S was kept low in order to permit higher blended sludge concentrations to be obtained. The values used here ranged from 0.0046 to 0.01 calculated on a gas released basis. A common value for the air to solids ratio seen in the literature in connection with full scale units is 0.02 (Ettelt, 1964; Mayo, 1965; Jones, 1968).

D. Study of Rheological Properties

1. Description of Viscometer

The rheological properties of the activated sludges were

TABLE 3
TYPICAL BLENDING SCHEDULE FOR $A/S = 0.0046$

Pressure of Saturation	Batch Gas Release g/l	K	C_s mg/l	V_w/V_s	C_m mg/l
40	0.0517	0.089	5,000	0.45	3,470
			10,000	0.89	5,300
			15,000	1.34	6,430
60	0.0827	0.0556	10,000	0.556	6,430
			15,000	0.834	8,180
			20,000	1.12	9,440
			25,000	1.39	10,450
80	0.1079	0.0426	15,000	0.64	9,150
			20,000	0.852	10,800
			25,000	1.063	12,100
120	0.177*	0.0258	15,000	0.387	10,800
			20,000	0.516	13,200
			25,000	0.645	15,200

*Note: The recycle water for 120 psi was saturated by mechanical shaking.
Water at all other pressures was saturated by diffused air.

measured using a coaxial cylinder rotational viscometer. The viscometer consisted of two plexiglass cylinders aligned concentrically in the vertical position. The inner cylinder, the bob, was supported by a torsion wire, a 0.007 in. diam music wire 3 in. long. One end of the torsion wire was connected to a fixed external support while the other end was attached to a stiff rod which was connected vertically to the axis of the bob. The bob was weighted with a steel weight in order to keep it immersed when in use. The outer cylinder was mounted vertically on a hollow shaft which served as the means of rotation of the cylinder. The shaft, by means of a set of pillow blocks, was mounted on a rigid frame. The outer cylinder was driven via a belt-pulley system by a variable speed motor which was capable of providing a wide range of angular velocities. The speed of rotation was calculated from the number of impulses recorded by an impulse counter which was activated by a microswitch which closed with each 0.25 revolution of the drive shaft.

The diameters of the unlined cylinders were 1.24 in. and 1.75 in., respectively, for the bob and the cup. The surfaces of the cylinders were lined with a rubber matting^{*} to prevent slippage between the suspension and the smooth surface of the cylinders. It may be noted that the 0.27 in. gap between the cylinder walls is larger than normally used in commercial viscometers. Dick (1965) found this to be necessary to accommodate the sized particles associated with activated sludge. A short length of wire attached radially to the top of the bob served as a pointer. The deflection of the pointer was read in degrees from an externally supported scale which was aligned concentrically with the

* No. 3070 Neotex Protective Mesh distributed by Research Products Corporation, Madison, Wisconsin

outer cylinder. A dampening device consisting of paddles immersed in an oil bath was attached to the rod supporting the bob and served to dampen out oscillations in the deflection of the bob thus permitting readings to be made more rapidly. A schematic diagram of the viscometer is shown in Figure 13.

2. Calibration of Viscometer

In order for the data collected from the viscometer to be meaningful, the viscometer had to be calibrated using a fluid of known viscosity. One of the main factors which had to be considered in the calibration was the effect of the viscous drag on the end of the bob, i.e. the determination of the end effect. Wang (1967) in his work with this viscometer showed that the end effect, h_o , was dependent upon the viscosity of the fluid being tested. The magnitude of the end effect decreased as the viscosity of the fluid being tested increased.

In this study several Newtonian fluids of different viscosities were used in the calibration of the viscometer. The fluids used included an aqueous solution containing 10 percent glycerol by weight and 20, 40, and 60 percent aqueous solutions of sucrose. These fluids had viscosities ranging from 1.153×10^{-2} dyne sec/sq cm to 0.4386 dyne sec/sq cm at 25°C. The end effect varied with the viscosity as shown in Figure 14. While the diameters of the unlined cylinders were known, it was necessary to determine their effective diameters after having been lined so that the instrument constants which describe the geometric properties of the viscometer could be determined.

The calibration was performed according to the following procedure. With the bob raised so that the gap between it and the bottom of the outer cylinder was 1.5 in. the viscometer was filled with a

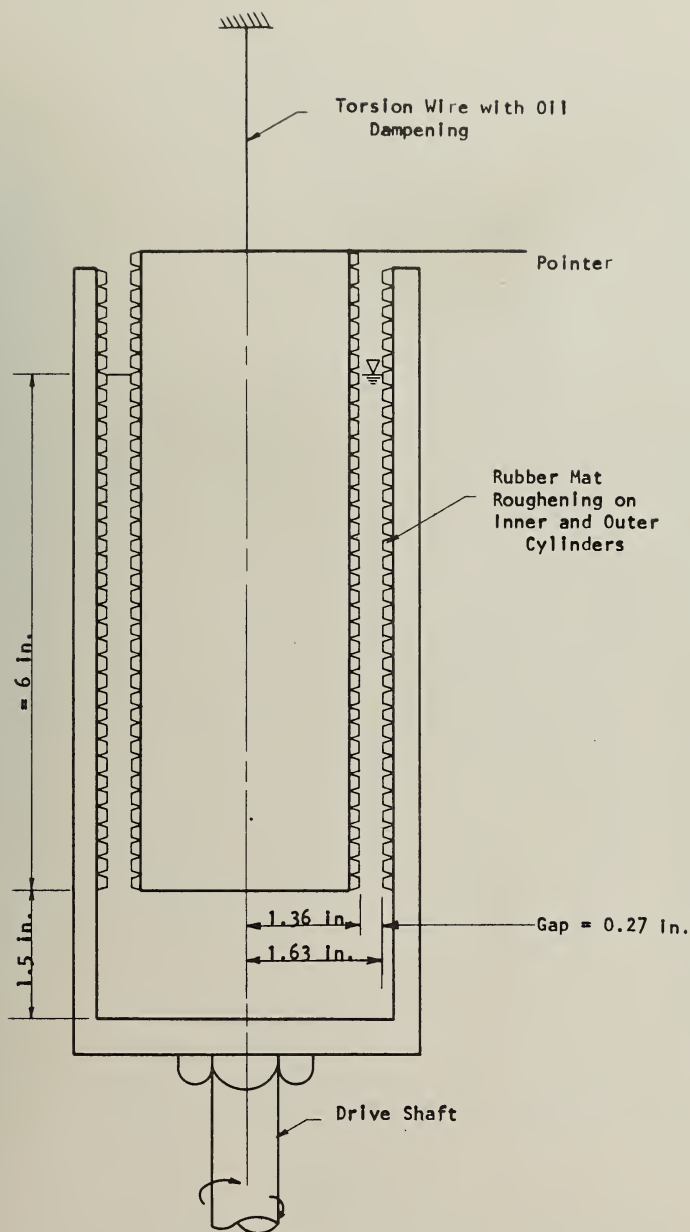


FIGURE 13. SCHEMATIC DRAWING OF COAXIAL CYLINDER ROTATIONAL VISCOMETER

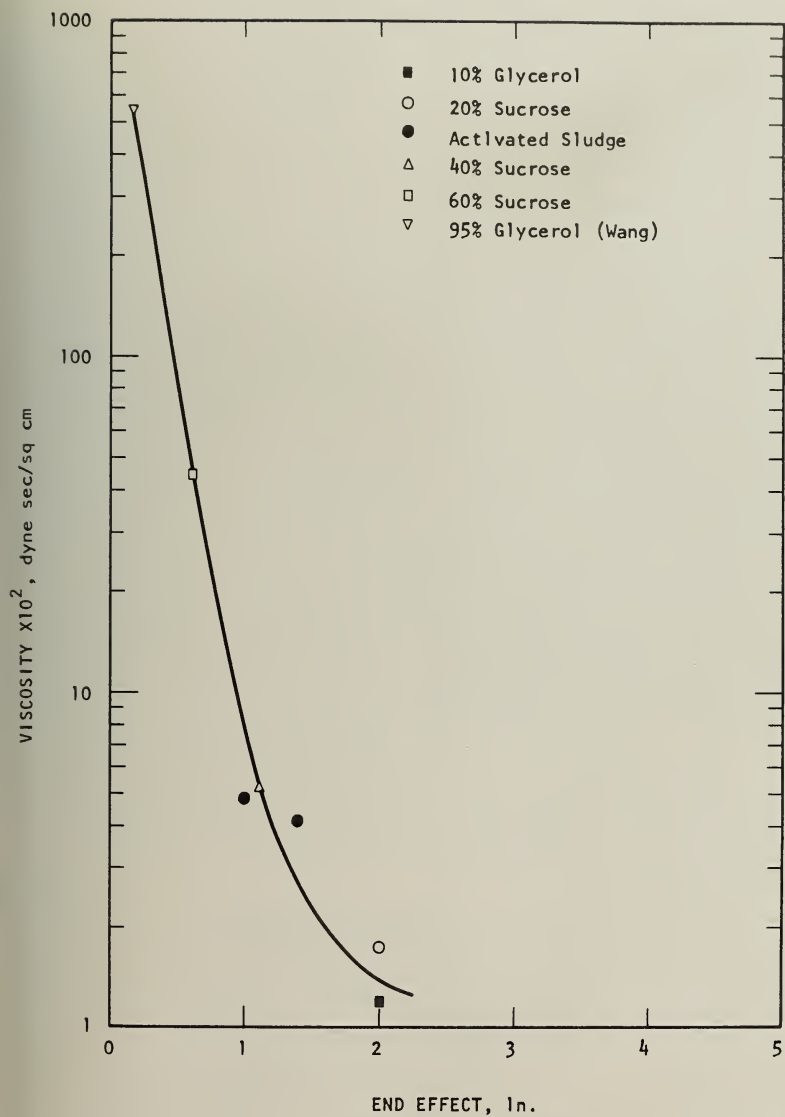


FIGURE 14. RELATIONSHIP BETWEEN VISCOSITY AND END EFFECT

Newtonian liquid until 6 in. of the bob were submerged. As the outer cylinder was rotated, the deflections of the inner cylinder, due to the torque applied by the shearing of the fluid in the annular space between the two cylinders, were recorded for a number of speeds of rotation. This procedure was repeated with the liquid level adjusted so that 4 and 5 in. of the bob were submerged. The data for all depths were then plotted as rotative speed versus deflection. The data for a typical calibration are shown in Figure 15. Both cylinders were lined during this calibration procedure. The reciprocals of the slopes were plotted against the depths of submergence as shown in Figure 16. A line drawn through these points and extrapolated to the h axis gave the value of h_o , the end effect. This procedure was followed with each of the Newtonian fluids. The spring constant for the torsion wire was calculated using laboratory experimental data and data provided by the manufacturer of the wire, National Standard Co., Niles, Michigan. The only remaining unknown was the effective thickness of the matting. This was calculated using the following equation (Wang, 1967):

$$\frac{\theta/\Omega}{h + h_o} = \frac{8 \pi^2 \mu}{\alpha} \left[\frac{1}{(R_i + \delta)^2} - \frac{1}{(R_o - \delta)^2} \right]^{-1} \quad (8)$$

where

$$\theta/\Omega = \frac{\text{deflection, degrees}}{\text{rotative speed, rpm}}$$

$$h + h_o = \text{depth of submergence} + \text{end effect}$$

$$\mu = \text{viscosity of the Newtonian fluid}$$

$$\alpha = \text{torsional spring constant}$$

$$R_i = \text{radius of inner cylinder, unroughened}$$

$$R_o = \text{radius of outer cylinder, unroughened}$$

$$\delta = \text{effective thickness of the matting}$$

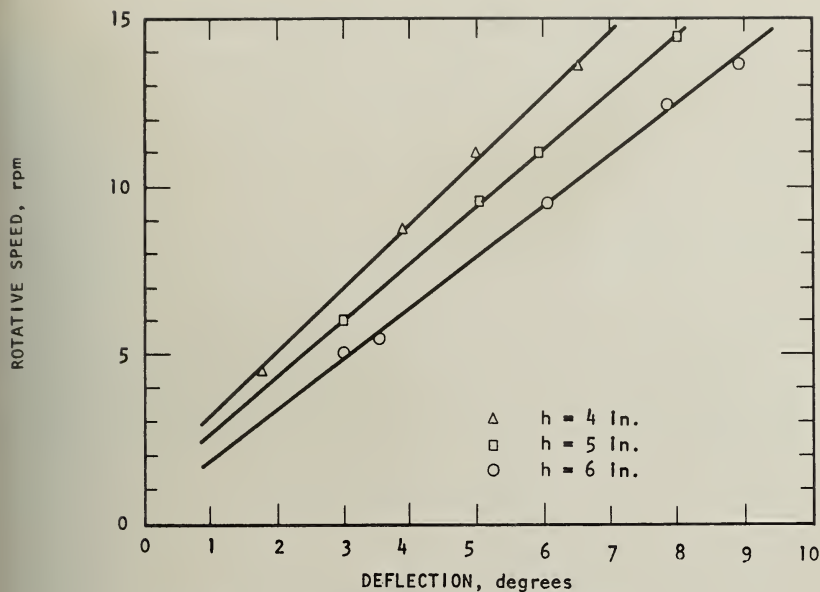


FIGURE 15. VISCOMETER CALIBRATION CURVES

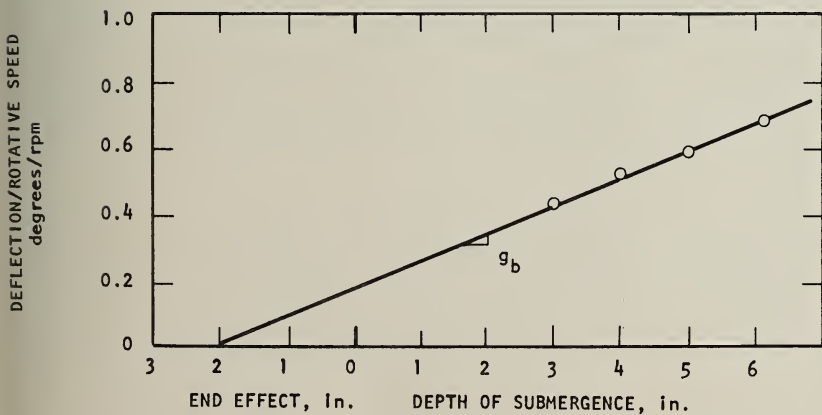


FIGURE 16. DETERMINATION OF END EFFECT

For a given viscometer all of its geometric characteristics may be combined into one constant, K_A , (Green, 1949). For a Newtonian fluid the viscosity, μ , may be calculated from the expression:

$$\mu = K_A \frac{T}{\Omega} \quad (9)$$

where T is the torque and Ω is the angular velocity in rad/sec. Torque may be calculated using the expression

$$T = \alpha \theta \quad (10)$$

where α is the torsional spring constant and θ is the deflection in degrees. The constant K_A can be calculated from the following expression:

$$K_A = \frac{1}{4\pi (h + h_0)} \left(\frac{1}{R_i^2} - \frac{1}{R_o^2} \right) \quad (11)$$

where R_i^1 and R_o^1 are the effective diameters of the roughened cylinders.

Activated sludge has been shown to behave as a Bingham plastic, that is, the rate of shear is directly proportional to the shearing stress once the yield value has been exceeded (Dick, 1965) (Dick and Ewing, 1967). Unlike Newtonian liquids, a substantial angular velocity is required in order to obtain complete shear across the gap in the viscometer. The yield strength may be calculated using this expression:

$$\tau_y = K_B \theta_X \alpha = K_B T_X \quad (12)$$

where τ_y is the yield strength and θ_X is the intercept on the deflection axis obtained by extrapolating the straight line portion of the consistency curve. K_B is an instrument constant.

$$K_B = \frac{K_A}{\ln R_o^1/R_i^1} \quad (13)$$

The plastic viscosity, the slope of the straight line portion of the consistency curve, may be calculated as follows:

$$\eta = K_A \frac{T - T_x}{\Omega} \quad (14)$$

where Ω is in rads/sec.

Since the end effect was found to be dependent upon the viscosity of the material being tested, the instrument constants K_A and K_B also varied with the viscosity. Using the curve of Figure 14 which shows the relationship between viscosity and end effect, the instrument constants were calculated using a trial and error procedure. A trial value of end effect was selected and used to calculate a value of K_A . The plastic viscosity of a sample was calculated using that value of K_A . The plastic viscosity obtained was applied to Figure 14 to see if the corresponding value of end effect was the same as the selected one. The procedure was repeated until agreement between the end effect values was achieved. When agreement was reached, the K_A value for that end effect was used to compute the value of K_B .

The values of the spring constant and effective thickness of the cylinder linings were

$$\alpha = 17.4 \text{ dyne cm/degree}$$

$$\delta = 0.30 \text{ cm}$$

Typical values of the instrument constants were

$$K_A = 1.182 \times 10^{-4} \text{ cm}^{-3}$$

$$K_B = 6.18 \times 10^{-4} \text{ cm}^{-3}$$

3. Experimental Procedure

Activated sludge of known concentration was introduced into the viscometer by pouring it from the top into the annular space between the

two cylinders. A volume of sludge sufficient to submerge the lower 6 in. of the bob was used in all cases. The sludge was redistributed by bubbling air through the hollow drive shaft and into the viscometer at a rate which would generate the turbulence needed to provide good mixing. A mixing period of about 10 sec was used. Dick (1965) determined that a period of about 45 sec was sufficient to permit reflocculation of the sludge. A similar period was used here. Following the period of reflocculation the motor was started to rotate the outer cylinder. As the inner cylinder began to rotate its motion was restricted manually in an attempt to reduce the magnitude of the initial oscillation of the bob. The deflection as indicated by the pointer after it became somewhat steady was read and recorded, usually within the first 20 to 30 sec after the start of rotation. The speed of rotation was calculated using the counter and a stop watch. The sludge was redistributed again and the process was repeated at another speed. This procedure was repeated at several speeds until sufficient points were available so that the consistency curve could be drawn. The same routine was followed using at least 2 other concentrations of the same sludge. The data were plotted and the values for yield strength and plastic viscosity were calculated using the appropriate formulas presented in the preceeding section. Plots of typical data are shown in Figure 17.

E. Removal of Extracellular Polysaccharide

The extracellular polysaccharides associated with bacteria are present in the form of sheaths or capsules (Wilkinson, 1958). A number of procedures have been used to remove these materials for study. Chemical extractions have frequently been used in work with bacterial

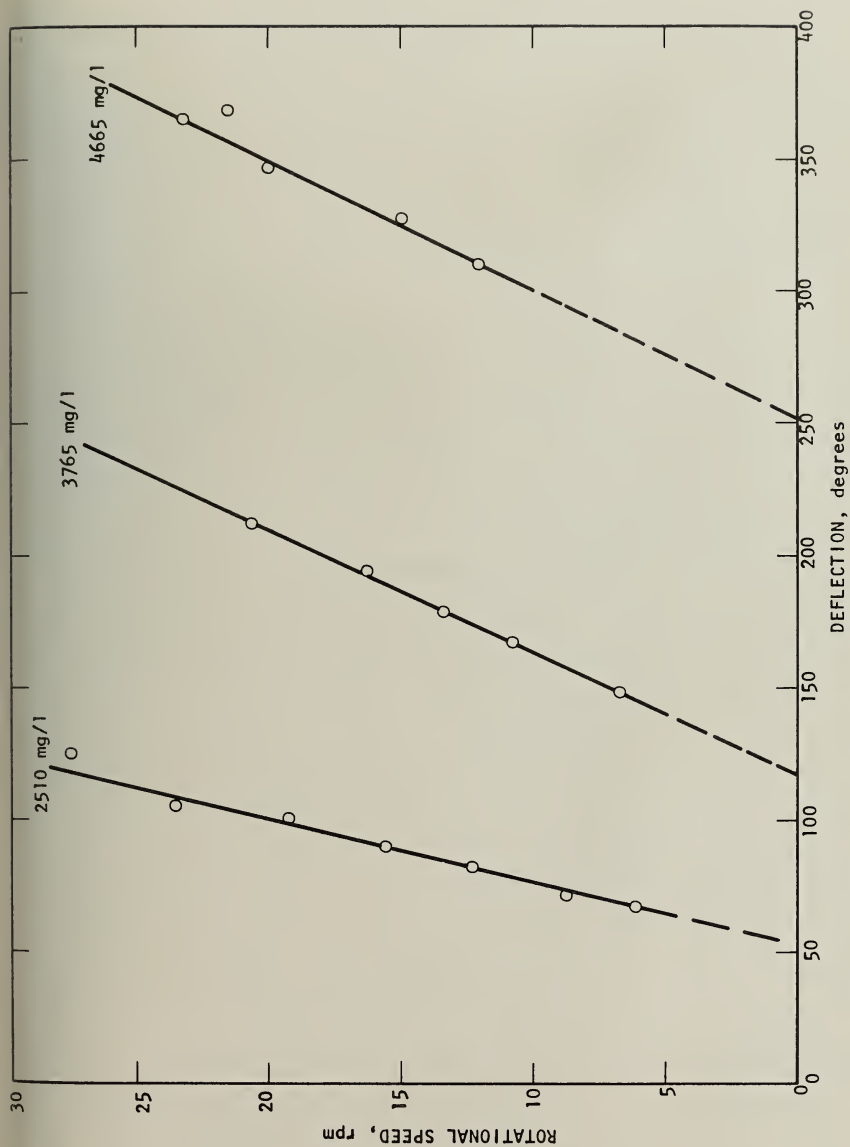


FIGURE 17. TYPICAL VISCOMETER DATA

polysaccharides. Phenol and water, trichloroacetic acid, sodium hydroxide and acetic acid are some of the reagents commonly used in performing these extractions (Luderitz et al., 1966). Recently Nishikawa and Kuriyama (1968) and Takiguchi (1968) reported extracting a material which they called mucilage from activated sludge using Na_2CO_3 and NaOH . The mucilage was found to contain about 35 percent deoxyribonucleic acid with the balance being mostly polysaccharide.

Methods employing shearing have been used in a number of studies as a means of mechanically stripping the extracellular polysaccharides from the cells. Juni and Heym (1964) removed capsular material by passing a bacterial cell suspension through a glass chromatogram sprayer 3 or 4 times. Gaudy and Wolfe (1962) recovered the slime from Sphaerotilus natans by blending a suspension of the washed cells in a laboratory blender and separated the cells from the slime by centrifugation. Szaniszló et al., (1968) used high speed blending in a Waring blender to remove the capsular polysaccharide from a marine filamentous fungi. Conrad (1969) described a method to be used for the isolation of polysaccharides from gram-negative cells. He, too, recommended the use of agitation at top speed in a Waring blender as a means of stripping extracellular polysaccharides from cells harvested while in the late log growth phase. Exposure to ultrasonic sound is another method which has been used to physically shear this material from the cell wall. Freidman et al. (1968) used exposure to ultrasonic sound to remove the matrix surrounding the cells in their pure culture of Zooglea ramigera. Wyss et al. (1968) used exposure to ultrasonic sound to strip capsular material from hydrocarbon utilizing bacteria. In all of the above cases, once the capsular material had been stripped from the cells it was

separated from the cells and debris by centrifugation at forces of from 3,000 to 20,000 g, usually in refrigerated centrifuges. The supernatant containing the polysaccharide was usually acidified and treated with cold alcohol or acetone to precipitate out polysaccharides. The precipitate was usually treated further depending upon the purpose of its recovery.

After some experimentation with the methods employing blending and exposure to ultrasonic sound, the blending method of stripping the extracellular material was chosen as the method to be employed in this study. Activated sludge washed twice with deionized water was resuspended in deionized water. The washed sludge was blended at top speed for 5 min in a Sorvall Omni-Mixer.* The sample container was immersed in an ice water bath to keep the temperature of the sample as low as possible. The blending time was selected after making microscopic examinations of sludges which had been blended for various lengths of time. Even after 10 min of blending, the activated sludge floc, though smaller in diameter, were still not completely dispersed. The blended sludge was centrifuged in a refrigerated centrifuge at 10,000 rpm for 20 min, the supernatant was decanted and centrifuged again. Samples of the supernatant were taken for total carbohydrate analysis using the anthrone method (Gaudy, 1962) (Snell et al., 1961).

F. Analytical Procedures

1. Chemical Oxygen Demand

The chemical oxygen demand (COD) tests performed on the feed,

*Cat. No. OM-115/X0, manufactured by Ivan Sorvall Inc., Norwalk, Connecticut

the effluent, and the mixed liquor solids were carried out according to the procedure described in the 12th edition of Standard Methods (1965). Twenty ml samples together with the indicated amounts of potassium dichromate, mercuric sulfate, and sulfuric acid containing AgSO_4 were used in most cases. For the determinations made on the mixed liquor solids, 40 ml samples were used together with the appropriate amounts of reagents. All analyses were made in duplicate and were refluxed for at least 2 hrs.

2. Organic and Ammonia Nitrogen

Organic nitrogen analyses were made using the Kjeldahl nitrogen procedure described in the 12th edition of Standard Methods (1965). The sample sizes varied depending upon the expected nitrogen content of the sample. The sizes of samples were selected so that, upon completion of the distillation, the pH of the distillate-boric acid solution would not exceed 7. Analyses were made in triplicate using duplicate blanks. One departure from the described method was the use of a pH meter rather than the mixed indicator in the titration of the distillate. The distillate boric acid solution for each sample was titrated back to the pH of the distillate-boric acid solution of the blank using 0.02 N HCL.

The ammonia nitrogen determinations were made according to the procedure given in Standard Methods (1965) with the exception that 0.02 N HCL was used as the titrant.

3. Suspended Solids Determination

The suspended solids determinations were made using the Gooch crucible-glass fiber filter method (Gratteau and Dick, 1968). This method utilized a 2.1 cm diam glass fiber filter mat^{*} as the filter media rather

*Glass Fiber Filter: Grade 934AH glass fiber filter 2.1 cm diam, a product of Reeve Angel and Company, Clifton, New Jersey

than the asbestos mat recommended in Standard Methods (1965). Gratteau and Dick (1968) have shown the Gooch crucible-glass fiber filter method to be more accurate than, and of comparable precision to, the standard Gooch crucible-asbestos mat and membrane filter techniques. The method for determining suspended solids concentrations using the glass fiber filter is essentially the same as the standard method. The filter mat is placed in a clean Gooch crucible, seated by filtering through a few ml of deionized water, dried in an oven at 103°C for at least 1 hr, cooled in a desiccator for 40 min and tared. After the sample has been filtered with the aid of a vacuum, the crucible is again cooled in a desiccator for 40 min and weighed. The suspended solids concentration is then calculated. Individual desiccators consisting of wide mouth bottles partially filled with silica gel and having a piece of plexiglass tubing to support the crucibles above the desiccant were used for cooling and storing the crucibles prior to weighing. For mixed liquor suspended solids determinations 10 ml sample sizes were used. The time required for filtration varied depending upon the properties of the sludge being filtered. For suspensions having lower concentrations of solids than mixed liquors, the sample sizes could be increased several fold.

4. Sludge Volume Index

The sludge volume index (SVI) measurements were made as described in Standard Methods (1965). The sludge volume index is defined as follows:

$$\text{Sludge Volume Index} = \frac{\text{ml settled sludge}}{\text{g suspended matter}} \quad (15)$$

One liter cylinders were used in performing the test. For the filamentously bulked sludges which settled slowly or not at all, the index was limited by the suspended solids concentration. In some tests the mixed liquor was

diluted with effluent from the flotation unit in order to obtain a sludge volume index for a MLSS of 1,000 mg/l.

5. Total Carbohydrate

The anthrone method was used to determine the carbohydrate content of the mixed liquor and of the extracellular polysaccharide material stripped from the cells (Gaudy, 1962; Snell and Snell, 1961). The anthrone reagent was made by dissolving 0.2 grams of anthrone in 100 ml of 95 percent H_2SO_4 and storing in an ice water bath. This reagent was made fresh a few hours before use. The tests were made using the following procedure: samples were appropriately diluted to a volume of 2.5 ml in test tubes with deionized water and were kept cold in an ice water bath. Five ml of cold anthrone reagent were pipetted into each of the test tubes. The anthrone reagent was quickly mixed with the sample in each tube immediately following the addition of the reagent to that tube. This was accomplished using a button ended glass rod or by vigorously striking the side of the tube with a finger several times. The tubes were kept in an ice water bath until all samples had been treated with the anthrone. The samples were then heated in a water bath at $100^{\circ}C$ for exactly 15 min. The tubes were capped with glass marbles immediately upon removal from the water bath and were placed in cold water (not ice water) so as to cool to room temperature. The marbles sealed the tubes preventing water or water vapor from entering the tube during cooling and causing the sample to become milky or turbid. The absorbances of the samples at 620 m μ were measured on a Beckman DU spectrophotometer using a one cm light path and a slit width of 0.08 mm. A 100 mg/l glucose solution preserved with 0.6 ml of commercial "Roccal"* per liter of glucose solution was used to

*Roccal (10 percent solution): A product of Winthrop Laboratories, New York. Active Ingredients: alkylid: methyl benzyl ammonium chloride (C_{12} , C_{14} , C_{16} and other related alkyl groups from C_8 to C_{18}) 10 percent inert. Ingredient: Water, 90 percent.

make the standard curve. Since the anthrone reagent was stable for only a few hours new standard curves were made each time a new volume of anthrone was prepared.

6. Float Solids Concentration

The concentration of solids in the float collected from the batch and continuous flotation cells were determined by placing a few ml of the sample in a tared glass weighing bottle, capping the bottle to prevent evaporation of water from the sample, and weighing. The cap was removed from the bottle and the sample was dried at 103°C overnight. After removal from the oven and cooling in a desiccator for one hr the sample was again weighed. The float solids concentration was calculated from these data and expressed as percent solids. The float solids determinations which were made in connection with the solids flux analysis were performed by withdrawing 50 ml of the concentrated sludge, diluting it 1:5 or 1:10 and then proceeding as in making a suspended solids determination.

7. Carbon to Nitrogen Ratio of Sludge Solids

The C:N ratio of the microorganisms making up the activated sludge was determined using a Hewlett Packard Model 185 C-H-N Analyzer^{*}. This instrument was designed to provide a rapid semiautomatic means for measuring the amounts of carbon, hydrogen, and nitrogen in organic materials. The instrument accomplishes this by converting the nitrogen, carbon, and hydrogen in the sample to N_2 , CO_2 , and H_2O in the presence of an oxidant at high temperature ($1,050^{\circ}\text{C}$). The products of combustion are swept into a gas chromatographic system by the flow of helium carrier gas. The gases are separated into discrete bands in the column. Upon emerging from the column the component bands enter a thermal conductivity detector which develops an electrical signal

^{*} Manufactured by Hewlett-Packard/ F & M Scientific Division, Avondale, Penn.

proportional to the concentration of the component in the carrier gas. The signal generated is delivered to a potentiometric recorder where the signal produces a chromatogram. The heights of the N_2 and CO_2 peaks are directly proportional to the amounts of nitrogen and carbon in the sample while the H_2O peak is related to the amount of hydrogen in the sample. Standard organic compounds having compositions similar to the samples to be analyzed are used to determine the relationships between the peak heights and the amounts of each of the 3 elements in the compound. The instrument has a built-in ratio recording feature which automatically attenuates the peak signals so that they are directly proportional to the sample weight. In other words, the signal is automatically divided by the sample weight so that the resulting peak heights of the chromatogram are directly proportional to the sample composition.

The instrument is capable of analyzing either liquid or solid samples. The sludge samples analyzed here were prepared for analysis as dried sludge solids. The solids in the mixed liquor from the aeration tank were washed, centrifuged and were dried for several hours at $103^{\circ}C$. The dry sludge was pulverized in a mortar and pestle to make a very fine powder. The powder was stored in an air tight plexiglass vial.

The size of the sample which could be used for analysis was limited to 0.5 mg - 0.7 mg. The sample was weighed in a tared platinum boat on the instrument's electronic balance. Following the weighing, the boat was positioned in the end of the combustion rod, packed with catalyzed oxidant and inserted into the combustion port of the instrument. A carrier gas bypass cycle of 20 sec was used as the sample was inserted into the combustion tube. The chromatogram was traced out on a Honeywell Elektronik 16 Strip Chart

Recorder^{*} using the automatic signal attenuation and ratio recording modes. Acetanilide, Cyclohexanane 2, 4-dinitrophenylhydrazone, and cystine were used as standards.

8. Photomicrographs

Routine microscopic observations and photomicrographs were made using a Carl Zeiss Standard RA microscope^{**} equipped with a phase contrast condensor. A 35 mm Zeiss Ikon attachment camera^{**} was used with the microscope for making photomicrographs. The ocular lens for the camera was a standard 10X eyepiece. Kodak Plus-X film was used. Flash illumination of 30 watt sec of energy was provided by the camera's microflash device. Combinations of filters having various degrees of light transmission were used to control the amount of light reaching the film during exposure. The film was developed for 5.5 min at 68°F using a fine grained developer.

^{*} Manufactured by Honeywell Industrial Prod. Group, Philadelphia, Penn.

^{**} Manufactured by Carl Zeiss, Oberkochen, Wuerтт., West Germany

IV. RESULTS AND DISCUSSION

A. Relationships Between Sludge Characteristics and Floatability

1. Shifts in Microbial Population

Initially it was planned that the characteristics of the activated sludge developed in the laboratory continuous flow system would be controlled by operating the system at steady state conditions. "Steady state" conditions as used here denotes operation of the system at conditions of constant F/M and BOD/N ratios. Shifts in sludge characteristics would be achieved when desired by changing the BOD/N and F/M ratios. As the work progressed, changes in the types of organisms predominating in the sludge occurred when shifts were not desired as well as when encouraged by the intentional changing of the loading and BOD/N of the substrate. The changes were determined by microscopic observation. Cassell et al. (1966) in their study of population dynamics and selection in continuously-fed mixed cultures observed shifts in populations in laboratory systems which were being operated at steady state conditions using skim milk as a substrate. This natural tendency toward population shift even under steady state conditions together with the operational problems encountered in this study when trying to maintain steady state conditions explain the population shifts which will be discussed in the following paragraphs.

Sludges were grown under three combinations of F/M and BOD/N ratios with the first being one where nitrogen was limiting, i.e. $F/M = 0.5$, $BOD/N = 40$. Since this was the first set of loading conditions, most of the problems with control of the BOD/N ratio were experienced under these conditions. Several shifts of population took place. The occurrence of the shifts could not be correlated directly with any operational changes or problems.

A filamentous type of organism having the appearance of a string of beads was the first to predominate the biomass at this loading. Typical filaments of this type are shown in Figure 18. After predominating for about three weeks this type of filament became less prevalent as a filamentous form of another type became predominant. This organism had individual cells arranged within the filament so that the long dimension of the cell was perpendicular to the axis of the filament. These filaments appeared to be similar to the ones which Pipes (1968) called Caryophanon. Typical filaments of this type are shown in Figure 19. It was interesting to note that often these filaments had cells attached externally at almost right angles to the long dimension of the filament. Filaments with these cells attached are shown in Figure 20. As these filaments diminished, odd shaped flocs were often formed as zooglear growth began to surround the old filaments. The flocs were often elongated with filaments serving as a sort of framework around which the flocs were organized. Such a floc is pictured in Figure 21. This filamentous growth was replaced by a predominantly zooglear sludge which predominated for a little more than a week. The Caryophanon-like type of sludge then returned and predominated until the loading rate was changed.

Following the shift of loading to $F/M = 1$ and $BOD/N = 25$ the Caryophanon-like type of filaments were surrounded by zooglear growth and diminished in numbers. Accompanying the zooglear growth were a significant number of long, straight, stiff filaments which showed some branching. This type of filament, whose presence may have been encouraged by a temporary oxygen deficiency, decreased in numbers over a period of 10 days or more. Filaments of this type are shown in Figure 22. The zooglear growth continued for a brief period before giving way to the string-of-beads type of filament which predominated until the loadings were changed. These filaments appeared

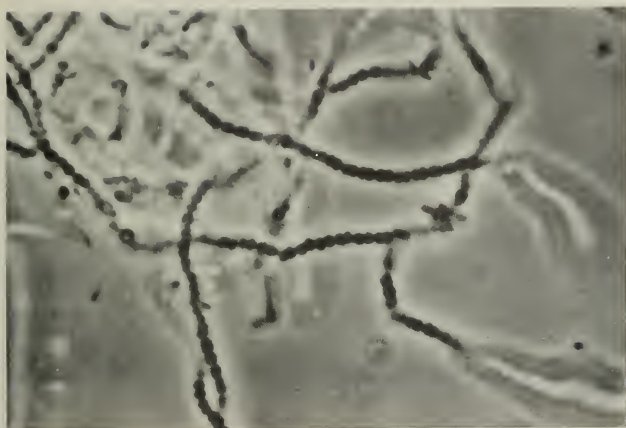


FIGURE 18. STRING-OF-BEADS TYPE OF FILAMENTS (x2160)



FIGURE 19. CARYOPHANON-LIKE FILAMENTS (x2160)

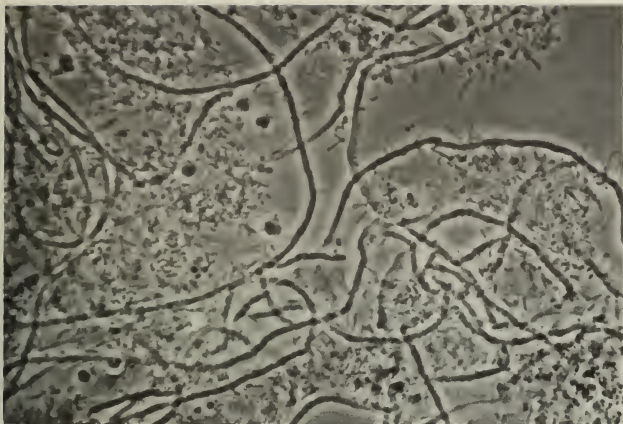


FIGURE 20. CARYOPHANON-LIKE FILAMENT WITH CELLS ATTACHED PERPENDICULARLY TO THE AXIS OF THE FILAMENT (x860)

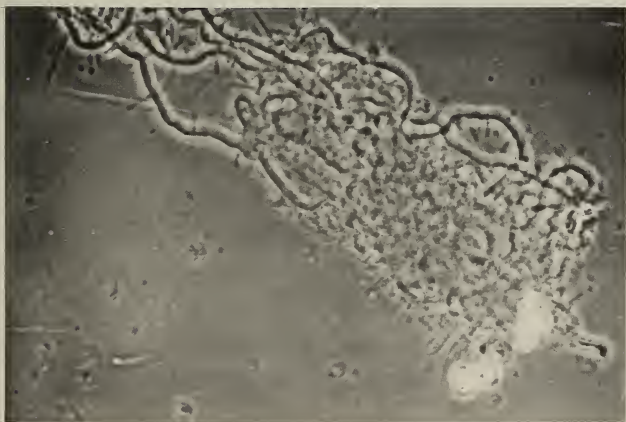


FIGURE 21. ELONGATED FLOC (x860)

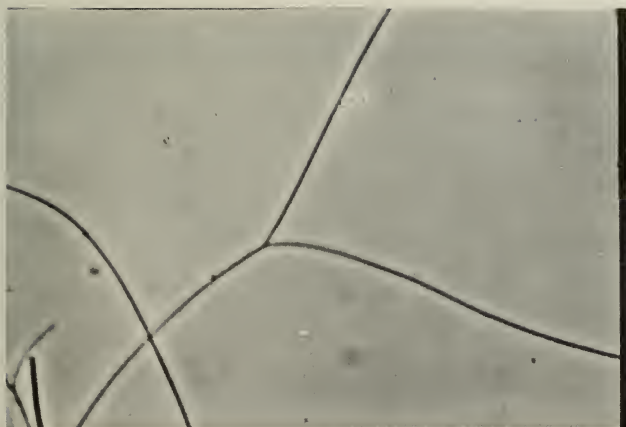


FIGURE 22. STIFF FILAMENT (x680)

to be the same or similar to the one which had been present in the system earlier under the first set of loading conditions.

The next combination was $F/M = 0.5$ and $BOD/N = 10$. With this combination nitrification with its accompanying decrease in the pH was a continuing problem. The quality of the sludge became poorer from a solids separation standpoint as the floc diameter decreased until floc practically ceased to exist. With the use of Na_2CO_3 it was possible to maintain the pH near 7.0 and finally the system was restored to a more normal condition. A zooglear type of sludge formed first and then was gradually replaced by the string-of-beads type of filament. Generally speaking, the operation of the continuous flow unit under these conditions was difficult, because of the poor separation characteristics of the sludge.

In addition to the sludges which were clearly filamentous or zooglear in nature there were many sludges which possessed various combinations of zooglear and filamentous growths. Interestingly enough, on some occasions when it might seem that the sludge was considerably more zooglear than filamentous on a mass basis, the presence of a few filaments would cause the sludge to exhibit properties more befitting a filamentous sludge.

The previous discussion has centered primarily around the types of organisms which made up the sludge floc. The presence of free swimming protozoans, stalked ciliates, and rotifers in the mixed liquor at all loadings should be mentioned. The numbers of these higher forms which were present seemed to vary widely with time. At times under a given loading they would be present in large number, yet within the space of a few days they would have almost completely disappeared.

While the seemingly continual shifting of the microbial population was not always predictable nor desired, it did provide an opportunity to

study the flotation of sludges of several different morphological types.

2. Effects of Percent Nitrogen and Carbon to Nitrogen Ratio of the Sludge Upon Flotation

Sludges possessing differing characteristics were obtained by changing the F/M and BOD/N ratios of the substrate as described previously. The following properties of the sludges were investigated with respect to their influence upon the flotation process: the amount of strippable extra-cellular polysaccharides, percentage of nitrogen in the sludge, the carbon to nitrogen ratio of the sludge, the morphology of the sludge, and the rheological properties, plastic viscosity and yield strength. The concentration of solids in the float and the sludge interfacial rise rate were used to evaluate the effects of these properties upon sludge flotation behavior. The batch test procedure described previously was used to perform these tests.

The first characteristic to be discussed is the percentage of nitrogen in the sludge. The amount of nitrogen in the sludge was determined both by the C-H-N analyzer and by the Kjeldahl method for organic nitrogen. Comparisons of the results obtained using the two methods indicate that the C-H-N analyzer gives values that are about 10 percent higher than the other method for sludges which were grown under nitrogen deficient conditions. The data presented here were obtained using the Kjeldahl method.

The data relating the percentage of nitrogen in the sludge to the solids concentration in the float after flotation had proceeded for 20 min are shown in Figure 23. These data indicate that in general higher float concentrations can be expected with sludges containing more than 8 to 8.5 percent nitrogen. Lower nitrogen concentrations resulted in lower float solids concentrations. The sludges which possessed higher concentrations of nitrogen were more likely to be zoogloeal while those of low nitrogen content were more filamentous. There were, as is clearly shown in the figure, some

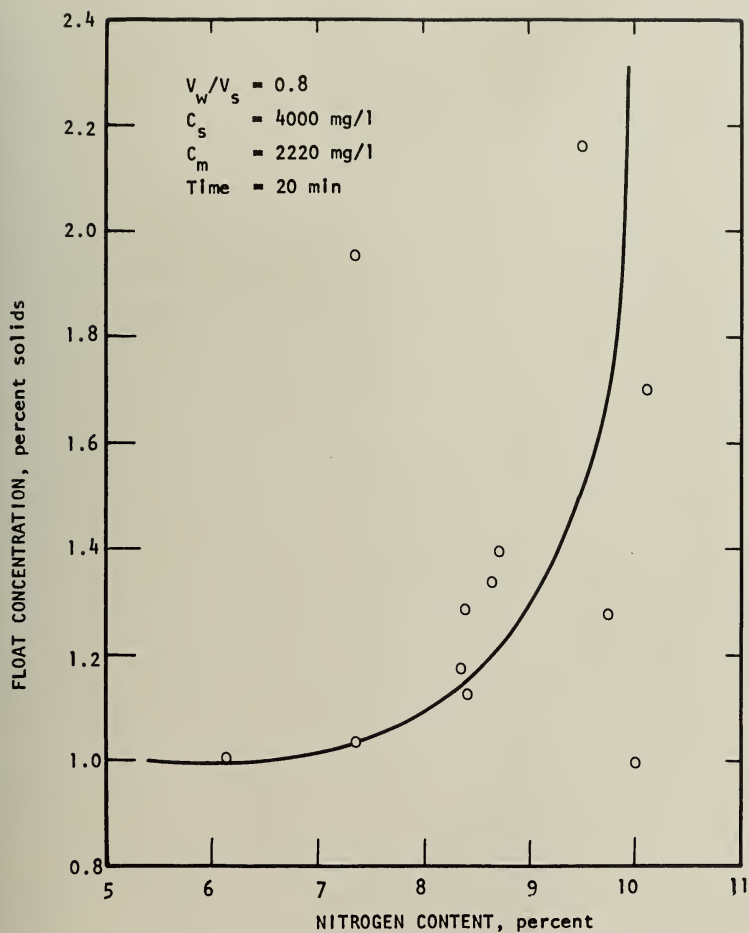


FIGURE 23. RELATIONSHIP BETWEEN NITROGEN CONTENT OF THE SLUDGE AND FLOAT CONCENTRATION

notable exceptions to these general statements. The data points plotted as showing a float concentration of about one percent and a nitrogen content of about 10 percent were obtained from a sludge which had been zoogleal but contained some filaments of the type shown previously in Figure 22. The behavior of this sludge in the flotation test was apparently dictated by these stiff filaments even though the sludge had a high nitrogen content indicative of a zoogleal type of growth. The next point above that one was obtained three days later after the stiff filaments had essentially disappeared and filaments of the types shown in Figures 18 and 19 were increasing in numbers. The point plotted as showing a sludge containing 7.35 percent nitrogen and yielding a float concentration of about 1.95 percent was obtained from a sludge which had been predominantly filamentous but was in a transition stage and becoming more zoogleal. In this case the characteristics of the zoogleal sludge apparently influenced the flotation behavior despite the relatively low nitrogen content.

The results obtained when the amount of nitrogen in the sludge is plotted against the rise rate are shown in Figure 24. Since a relationship exists between the interfacial rise rate and the solids concentration of the float the shape of this plot is somewhat similar to the previous one. The data points are quite scattered. As can be seen, there is not a good relationship between the rise rate and nitrogen content of the sludge.

The C/N ratios of the sludges were obtained using the data collected with the C-H-N analyzer. Since the values for the percentage of nitrogen in the sludge obtained with the analyzer differed considerably from the Kjeldahl data, it was possible to have two C/N ratios depending upon which value for the percentage of nitrogen was used. The data used here, however, are those

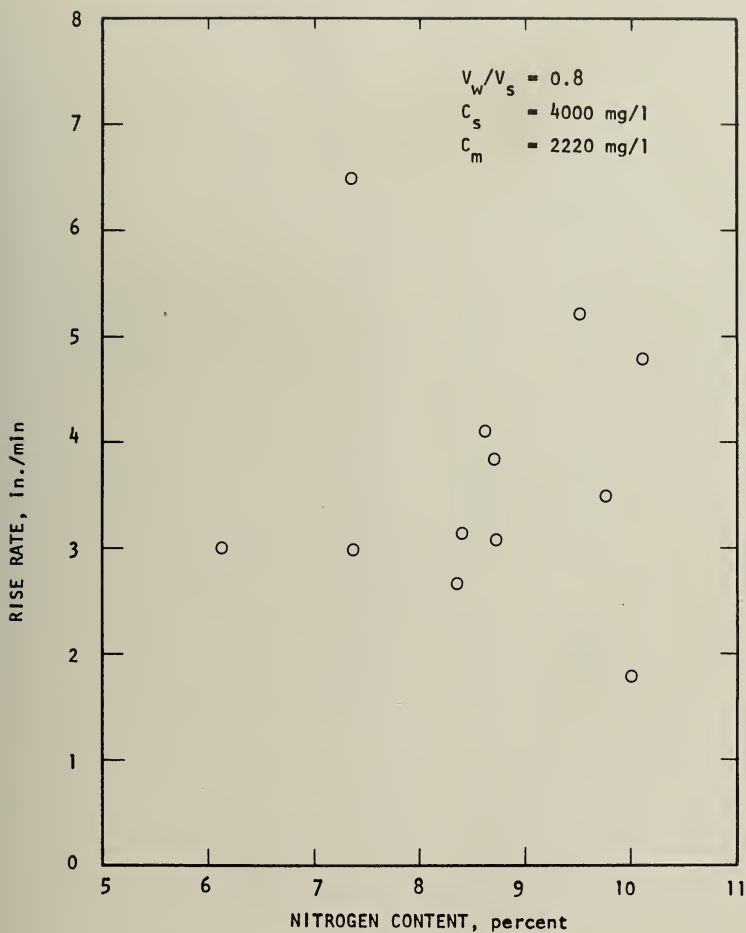


FIGURE 24. RELATIONSHIP BETWEEN NITROGEN CONTENT OF SLUDGE AND RISE RATE

obtained with the analyzer. The values obtained for a number of different sludges are shown in Table 4.

TABLE 4
C-H-N DATA FOR SEVERAL ACTIVATED SLUDGES

Date	%C	%N	%H	C/N
F/M = 0.5 BOD/N = 40				
7-20-69	42.5	6.5	7.6	6.5
7-29-69	41.0	8.3	7.1	5.0
8-11-69	39.5	6.7	6.75	5.9
8-17-69	40.5	5.31	6.9	7.6
F/M = 1 BOD/N = 25				
8-29-69	43.9	9.25	7.42	4.75
9- 4-69	46.8	9.74	7.54	4.81
9-15-69	44.5	9.5	7.53	4.68
9-22-69	43.2	7.72	7.38	5.58
9-19-69	43.0	8.8	7.52	4.89
F/M = 0.5 BOD/N = 10				
11-11-69	46.1	9.6	7.0	4.79
11-18-69	45.9	11.4	7.2	4.02
11-26-69	43.0	10.6	6.8	4.06

The C/N ratios of several of these sludges are plotted against their respective float concentrations in Figure 25. The data indicate that at best there is only a general trend toward higher float concentrations as the C/N ratio decreases. As with the nitrogen content data, the scatter in the data make the C/N ratio an unreliable indicator of float concentrations. A plot of the C/N ratio of the sludges against their rise rates, Figure 26, reveals that a good correlation does not exist.

3. Relationship Between the Presence of Extracellular Polysaccharide and Flotation Behavior

Extracellular polysaccharide was stripped from the activated sludge floc by the blending procedure described in the previous chapter. Even the

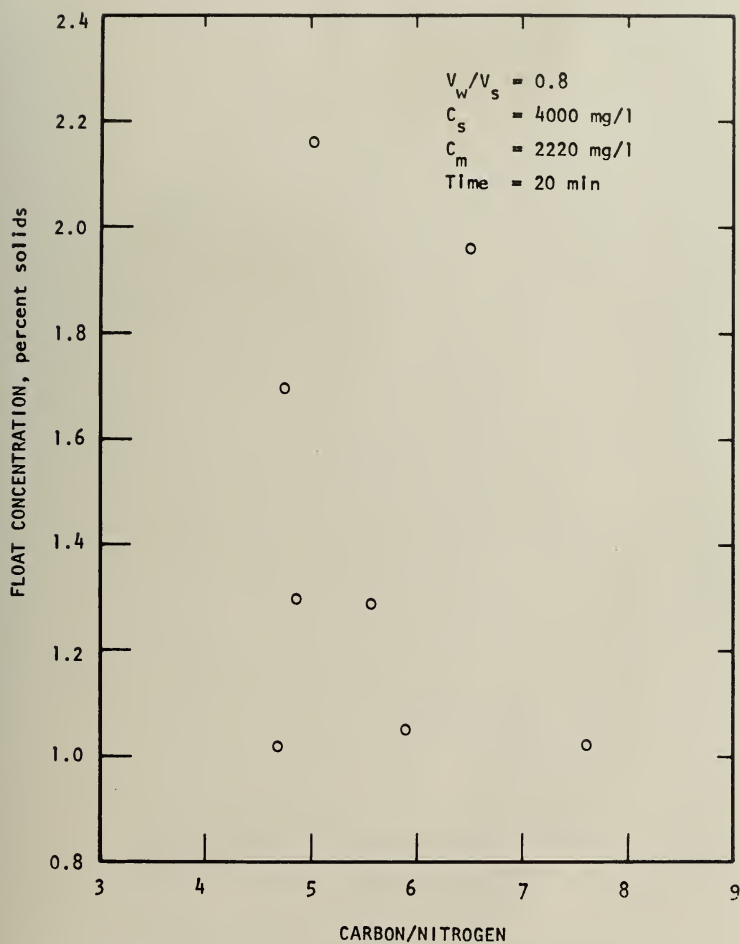


FIGURE 25. RELATIONSHIP BETWEEN CARBON TO NITROGEN RATIO AND FLOAT CONCENTRATION

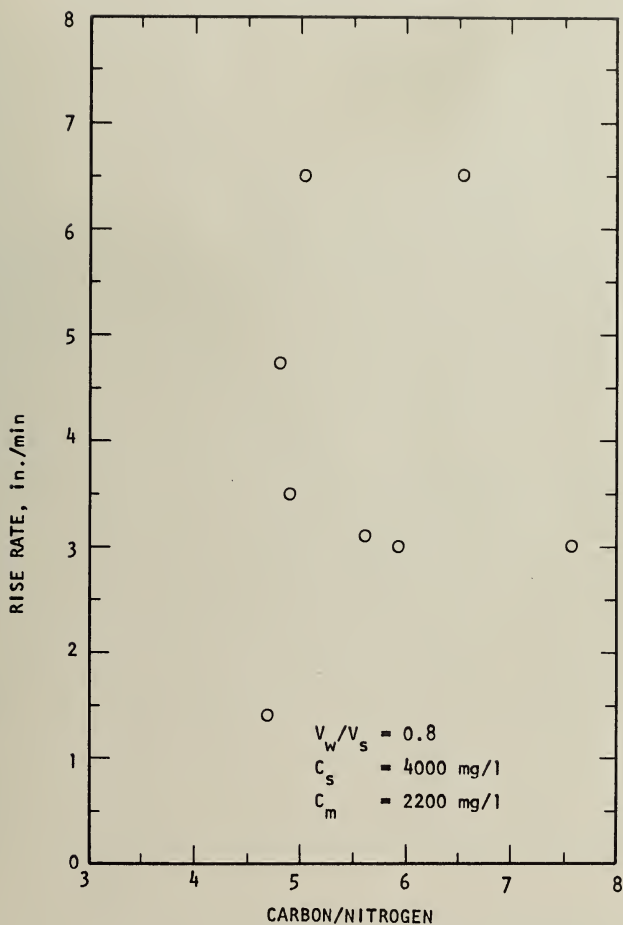


FIGURE 26. RELATIONSHIP BETWEEN CARBON TO NITROGEN RATIO OF THE SLUDGE AND RISE RATE

shearing of this blending operation was not sufficient to completely disperse the sludge floc. In view of this, the amount of polysaccharide recovered was probably something less than the total amount present extracellularly. The results obtained have been plotted against the appropriate parameters to determine their influence upon the flotation process. The data plotted in Figure 27 indicated that as the nitrogen content of the sludge decreased, the amount of extracellular polysaccharide seemed to increase. The extracellular polysaccharide data are plotted against the float concentrations and rise rates obtained as shown in Figures 28 and 29. In either case there does not seem to be a correlation between the results of the batch flotation tests and the amounts of extracellular polysaccharides stripped.

4. Rheology of the Activated Sludges

The rheological behavior of a suspension is dependent upon the characteristics of the materials in suspension as well as those of the suspending liquid. Activated sludges behave as Bingham plastics, that is, they possess yield strengths and have shearing stresses which are directly proportional to the shear rates once the yield stresses have been exceeded (Dick and Ewing, 1968). The physical characteristics of the microorganisms which make up the sludge are a major factor in determining the yield strength and plastic viscosity of a sludge. In this work the rheological properties of the sludges were used as a means of quantitatively characterizing the physical properties of the sludges.

The yield strength data for different types of sludges grown under various conditions in the laboratory have been plotted in Figure 30. As can be seen from this plot, the yield strength is quite dependent on sludge concentration. This type of data usually plot as straight or slightly curved lines on semilog paper in the 3,000 to 6,000 mg/l range of solids concentrations. As illustrated by curve B, the plot becomes slightly curved over a

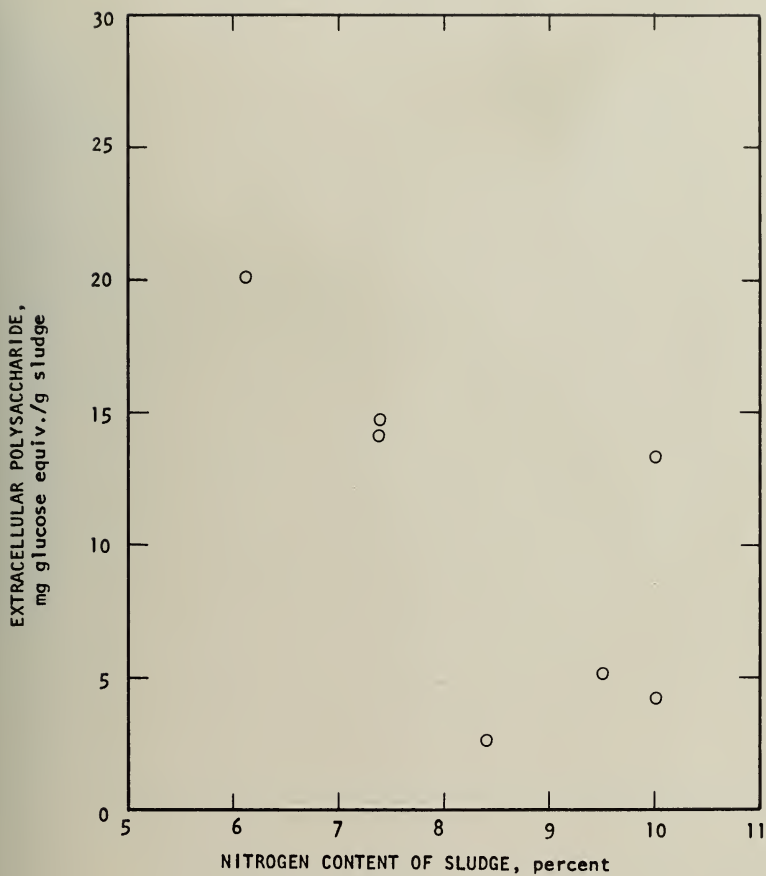


FIGURE 27. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND EXTRACELLULAR POLYSACCHARIDE

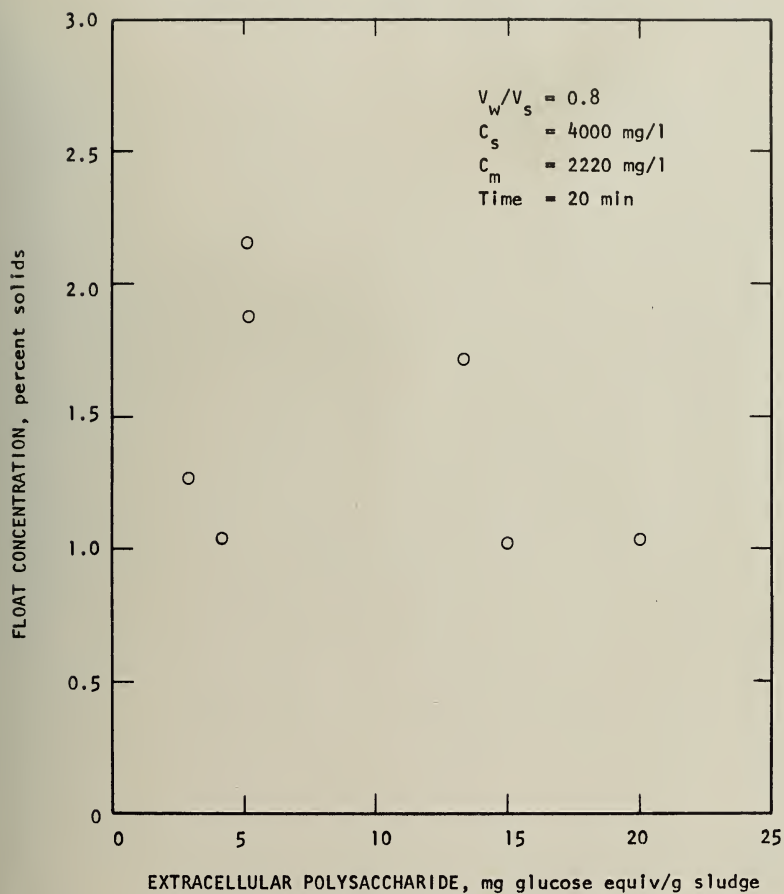


FIGURE 28. RELATIONSHIP BETWEEN EXTRACELLULAR POLYSACCHARIDE AND FLOAT CONCENTRATION

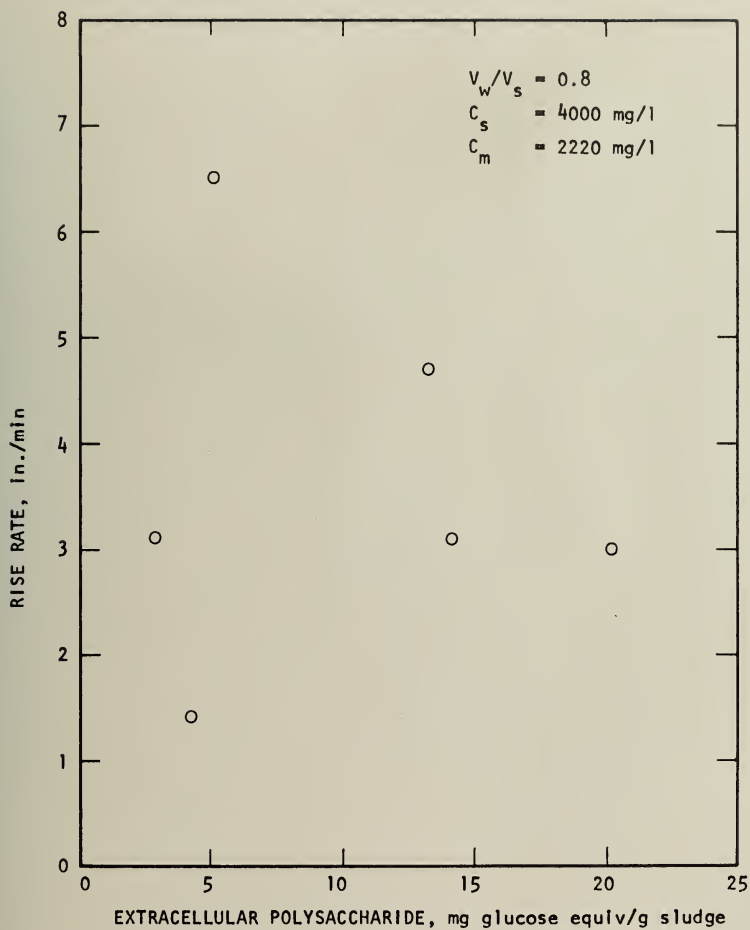


FIGURE 29. RELATIONSHIP BETWEEN EXTRACELLULAR POLYSACCHARIDE AND RISE RATE

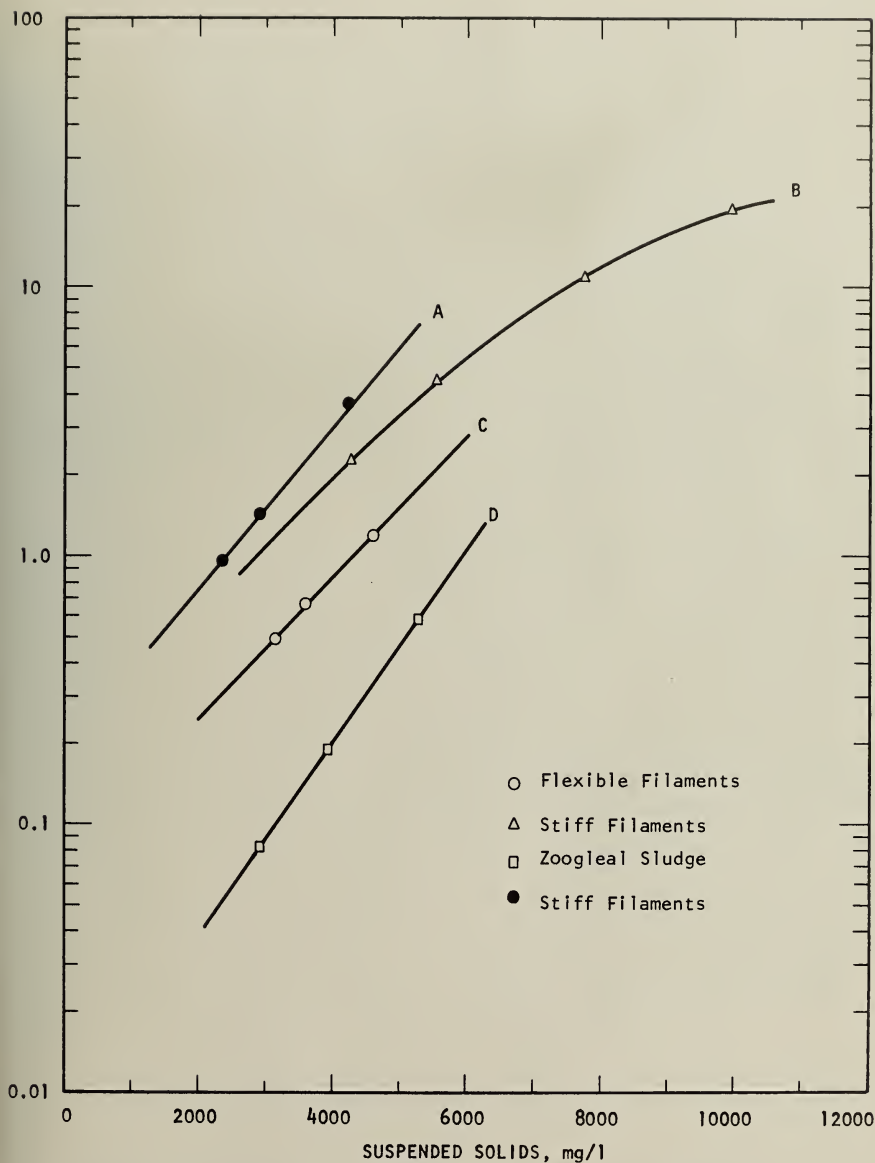


FIGURE 30. TYPICAL YIELD STRENGTH VALUES FOR ACTIVATED SLUDGE

wider range of suspended solids concentrations. Sludge A was grown at $F/M = 0.5$, $BOD/N = 40$ and was made up almost entirely of the type of organism being referred to here as resembling Caryophanon. A photomicrograph of this type of floc is shown in Figure 31. Sludge C was comprised primarily of those filaments similar in appearance to a string of beads as shown in Figure 32. The third, sludge D, was one which was essentially zoogeal and similar to that shown in Figure 33. It is interesting to note that the yield strengths of sludges A and D at concentrations of 4,000 mg/l differ by an order of magnitude. Between these two extremes, sludges possessing varying degrees of filamentousness provide yield strengths of intermediate magnitudes. The type as well as the quantity of filaments present appear to be reflected in the yield strength of the sludge. Microscopic observations revealed a possible reason why the sludges having filaments of the type represented in sludge C had yield strengths about half as great as those of the Caryophanon-like sludge. The string-of-beads type of filaments were much less rigid as was noted by its folding and bending when struck by floating debris while being observed on a microscope slide. The larger filaments of the Caryophanon-like sludge and the straight, stiff, filaments seen in other sludges possessed more rigidity and, therefore, contributed to higher yield strengths. The influence of the nature of the filaments on the rheological properties is dramatically illustrated by the ability of the presence of a relatively small number of filaments to give a predominantly zoogeal sludge a yield strength equal to that of the essentially filamentous sludge of type A.

The plastic viscosity data for the sludges described previously are plotted Figure 34. These data show that plastic viscosity was also dependent upon solids concentration and that sludges having high yield strengths also exhibited high plastic viscosities. For low solids concentrations, and over

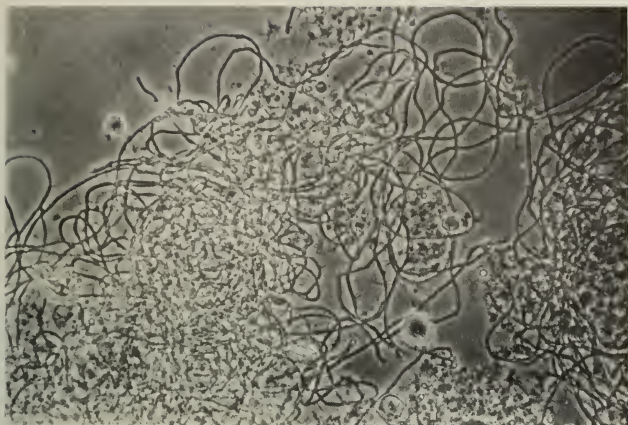


FIGURE 31. FLOC CONTAINING LARGE FILAMENTS
RESEMBLING CARYOPHANON (x340)

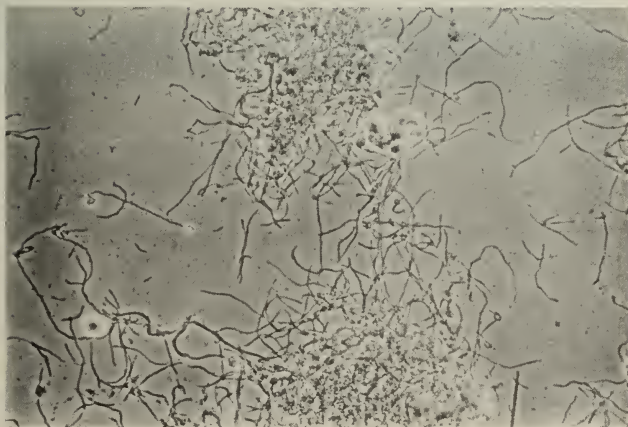


FIGURE 32. FLOC CONTAINING FLEXIBLE FILAMENTS (x340)

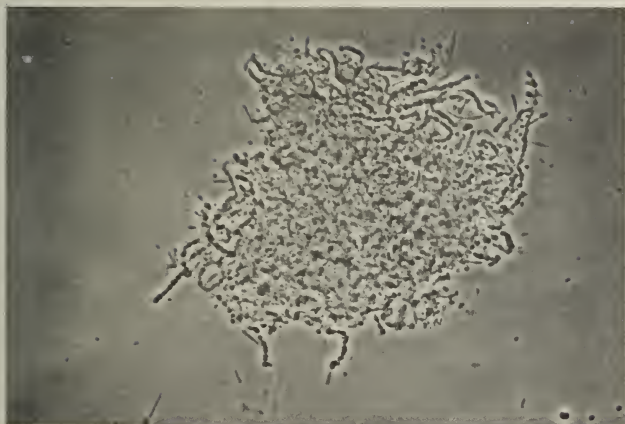


FIGURE 33. NORMAL ZOOGLEAL FLOC (x860)

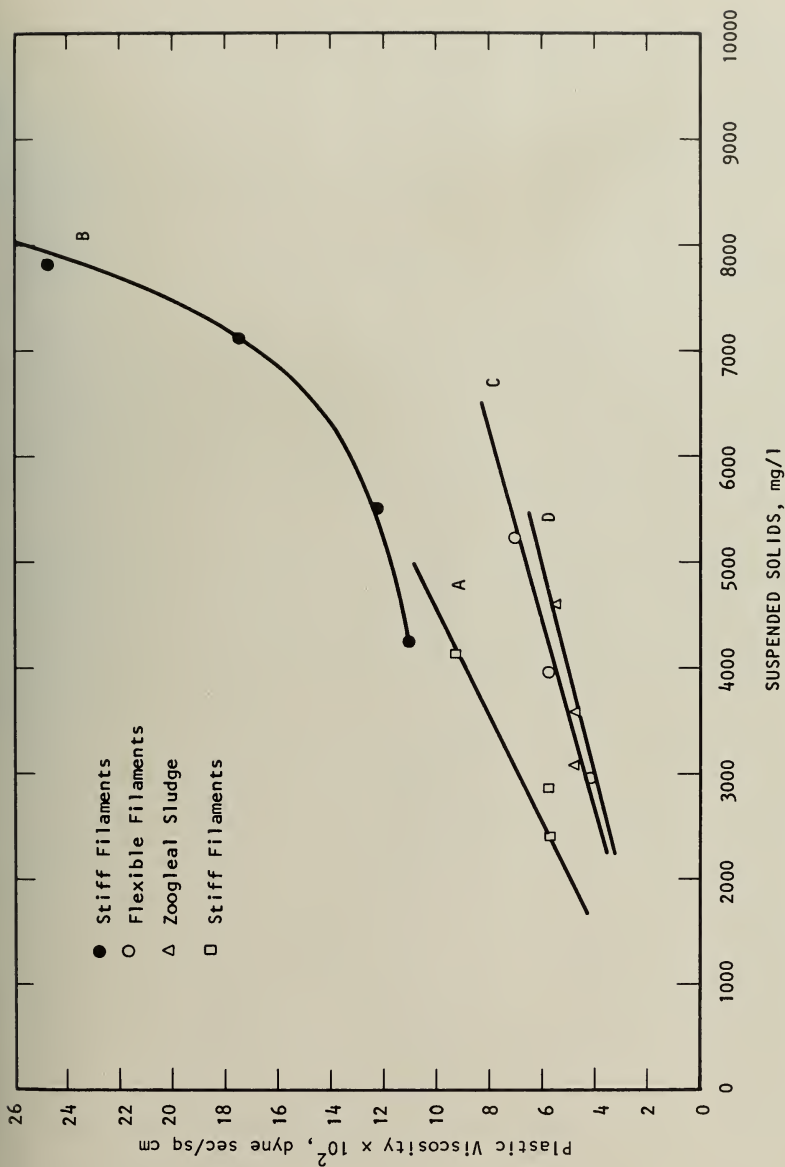


FIGURE 34. TYPICAL PLASTIC VISCOSITY PLOTS FOR ACTIVATED SLUDGES

the relatively short range of concentrations investigated, 2,500 to 5,500 mg/l, the relationship between solids concentration and plastic viscosity may fit Einstein's equation which relates the viscosity of a suspension to solids concentration. His equation is as follows:

$$\mu_s = \mu_l (1 + [\eta] C_v) \quad (16)$$

where

μ_s = viscosity of the suspension

μ_l = viscosity of the liquid

$[\eta]$ = intrinsic viscosity

C_v = volumetric solids concentration

The volumetric solids concentrations of the sludges used in this work were not determined. From Curve B it can be seen that at higher concentrations the relationship between solids concentration and plastic viscosity does not follow Einstein's equation.

5. Relationship of Rheological Properties to the Morphology and Nitrogen Content of the Sludge

The rheological properties of sludge are influenced to a large degree by the physical nature of the microorganisms which make up the sludge. The information obtained from the literature indicated that generally filamentous organisms, particularly the fungi, possess lower nitrogen contents than do zoogeal sludges. Therefore, it seemed important to determine whether or not a relationship existed between the nitrogen content of the sludges and their rheological properties. It had been hypothesized that the C/N ratio of the sludge might be a means of relating other sludge characteristics to the flotability of the sludge.

The sludges used in this study had nitrogen contents ranging from about 6 to 10 percent. The sludges which were almost totally made up of the Caryophanon-like organisms had nitrogen contents ranging between 6 and 7.5 percent. The flexible filamentous and zooglear sludges had nitrogen contents ranging from 8 to 10 percent with the flexible filamentous sludges generally being lower in nitrogen than the zooglear sludges. One sludge which was primarily zooglear but contained some straight stiff filaments had a nitrogen content of about 10 percent.

The yield strengths of several sludges are plotted against the percentage of nitrogen and the C/N ratios of the sludges in Figures 35 and 36. These data indicate that at yield strengths of 1.5 dynes/sq cm or less, yield strength generally increased as the nitrogen content increased. Sludges in this range of yield strengths were of the zooglear and flexible filamentous types of growth. At the higher yield strengths the data were widely scattered. The sludges having nitrogen contents of 6.1 and 7.4 percent were comprised almost entirely of the Caryophanon-like filament. The point representing a sludge containing 10 percent nitrogen has been discussed previously. This was the sludge comprised mainly of zooglear organisms but containing some long stiff filaments which are believed to have been responsible for the high yield strength of that sludge.

From the data presented it was concluded that at the lower yield strength values the yield strengths of the sludges are related to the nitrogen content and C/N ratio of the sludge. With the sludges which possess the higher yield strengths there is no apparent relationship between percent nitrogen, C/N and yield strength. Consequently, neither nitrogen content nor C/N by themselves can be considered reliable indicators of yield strength.

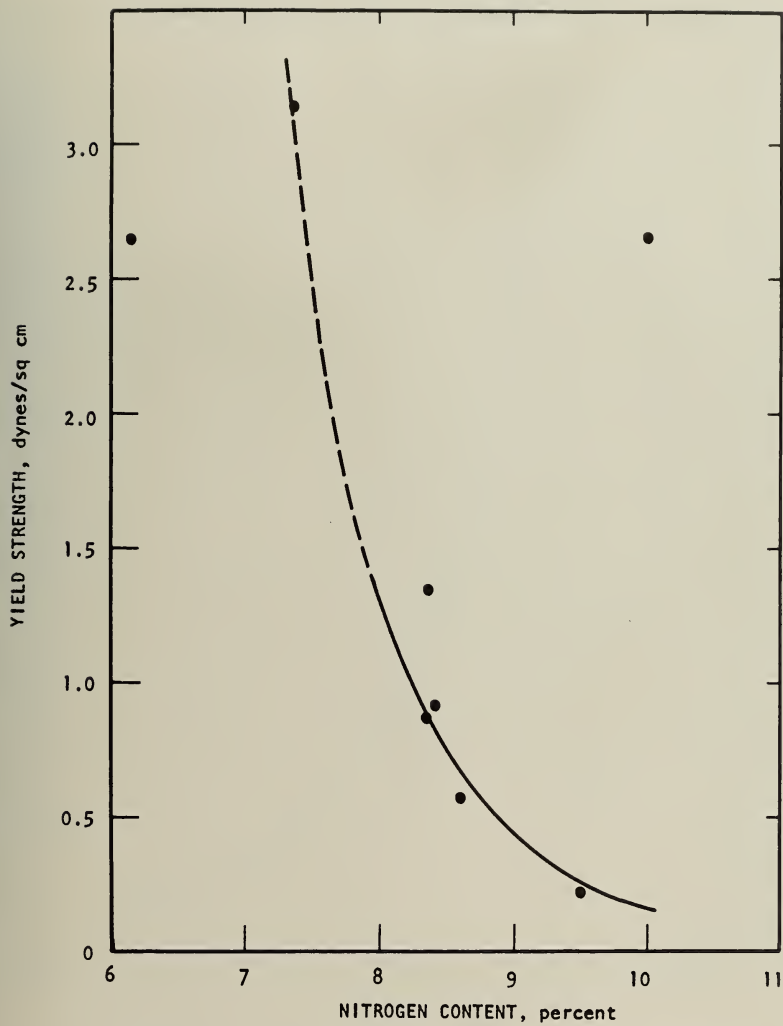


FIGURE 35. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND YIELD STRENGTH

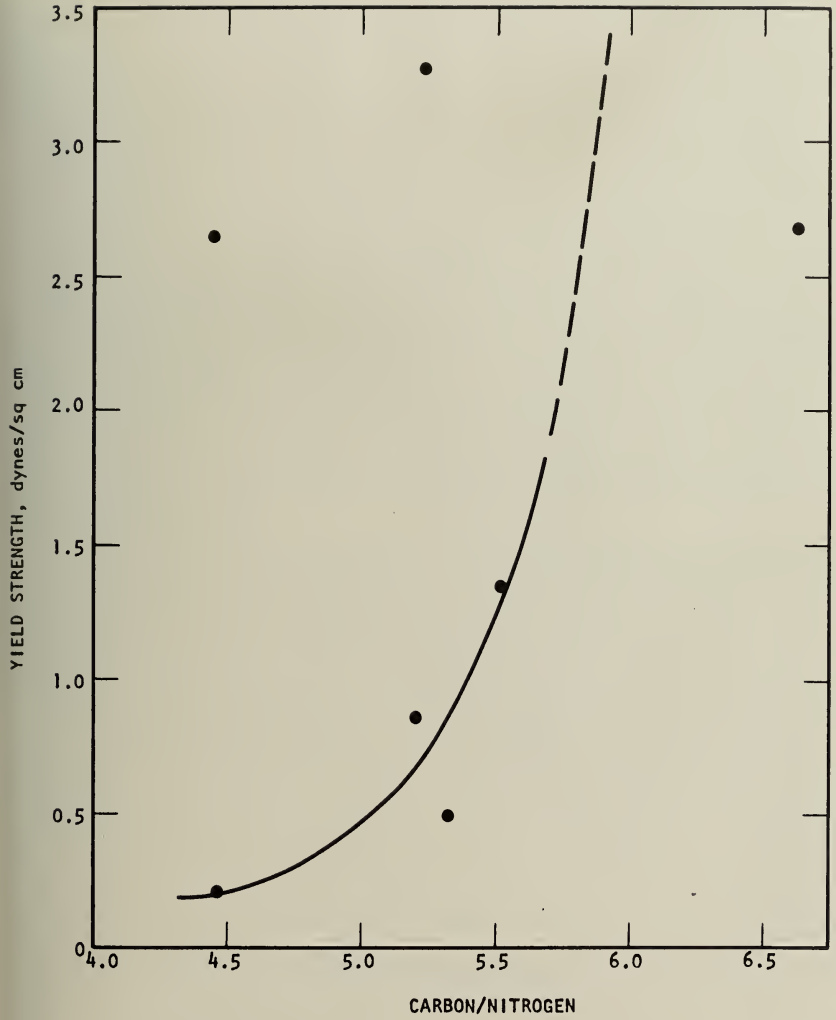


FIGURE 36. RELATIONSHIP BETWEEN THE CARBON/NITROGEN RATIO OF THE SLUDGE AND YIELD STRENGTH

Plots showing the plastic viscosity data plotted against the nitrogen content and carbon to nitrogen ratios of the sludges are presented in Figure 37 and 38. The plastic viscosity varies linearly with the nitrogen content of the sludge while the C/N data plot as a slightly curved line. The fit of the C/N data is not as good, however, as for the nitrogen data. These curves also reflect the morphological nature of the sludges. The sludges made up largely of the Caryophanon-like filaments contained the least nitrogen, the sludges having the string-of-beads type of filament had a higher nitrogen content and the non-filamentous sludges contained the most nitrogen. The percent nitrogen vs plastic viscosity curve slopes down to the right from the very filamentous sludges to the zooglear sludges. The C/N ratio vs plastic viscosity curve slopes up to the right from the zooglear to the filamentous sludges.

While there does not appear to be a good relationship between the nitrogen content of the sludge and the yield strength, there appears to be a good relationship between the nitrogen content and the plastic viscosity.

6. Relationship Between Rheological Properties and Flotation Behavior

The rheological properties of the sludges were found to differ widely during the course of this work. Batch flotation test data have also given various results depending upon the nature of the sludges. The relationship between the sludge yield strength and the float solids concentration obtained from batch flotation tests is shown in Figure 39. The yield strengths have been normalized to a suspended solids concentration of 4,000 mg/l. This concentration was chosen arbitrarily as the concentration to be used for comparing the yield strengths of the various sludges. The batch tests were performed in 2.5 in. columns according to the procedure outlined earlier. Tap water was used as recycle water in these tests. While it has been established

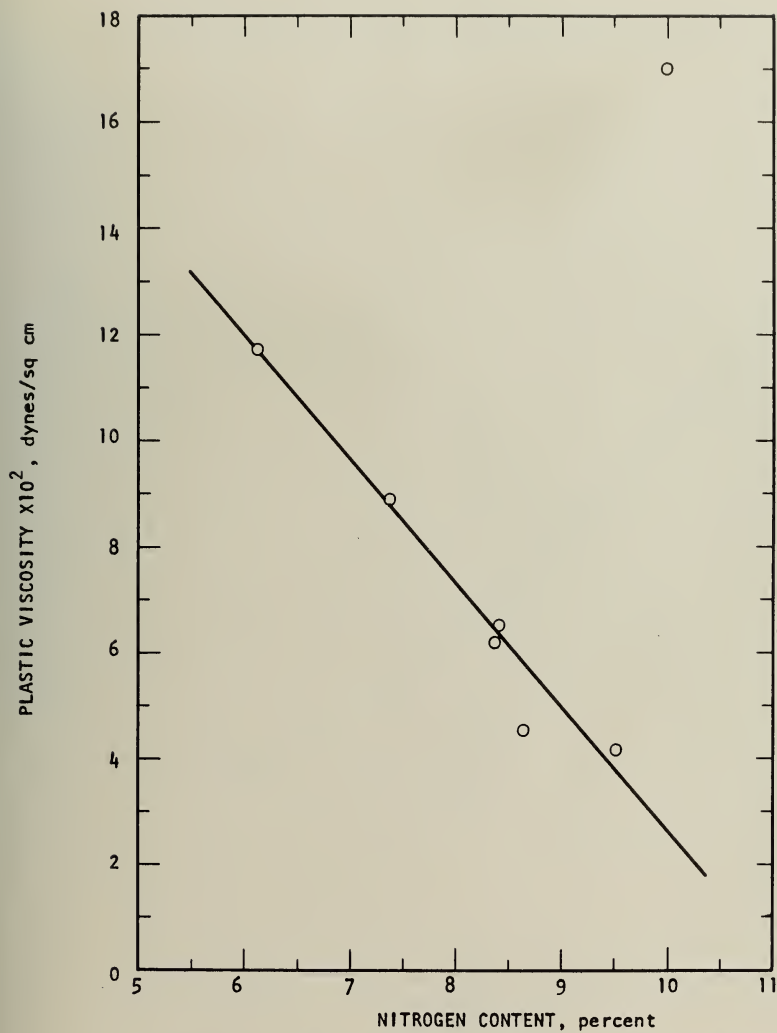


FIGURE 37. RELATIONSHIP BETWEEN THE NITROGEN CONTENT OF THE SLUDGE AND PLASTIC VISCOSITY

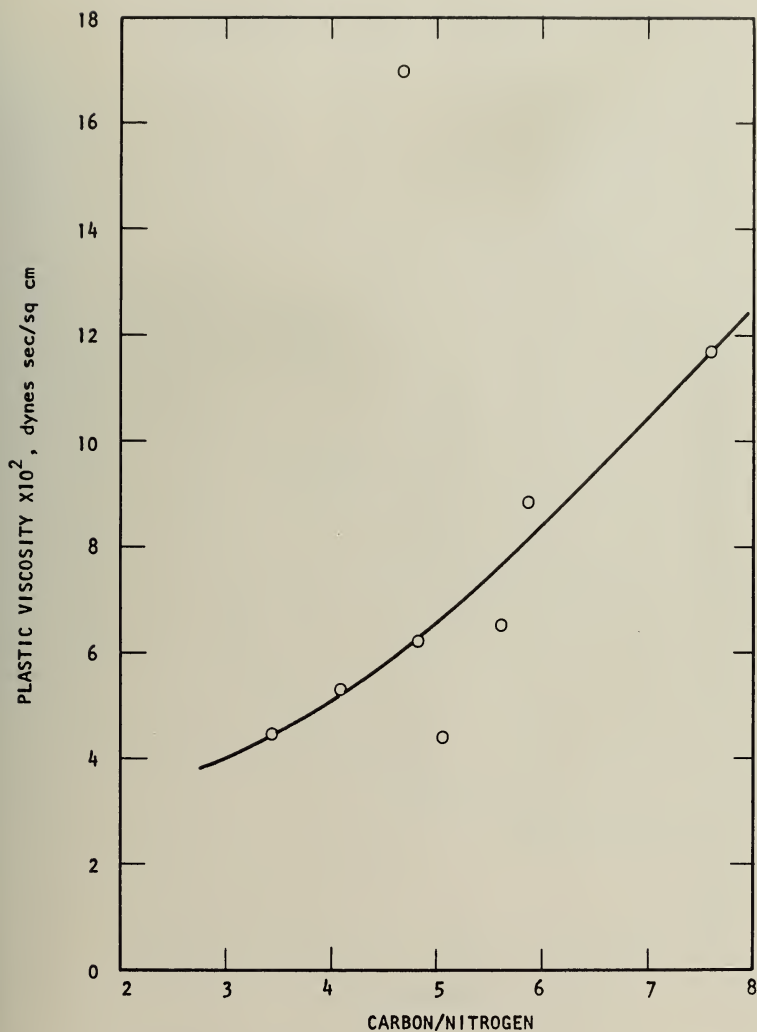


FIGURE 38. RELATIONSHIP BETWEEN PLASTIC VISCOSITY AND THE CARBON TO NITROGEN RATIO OF THE SLUDGE

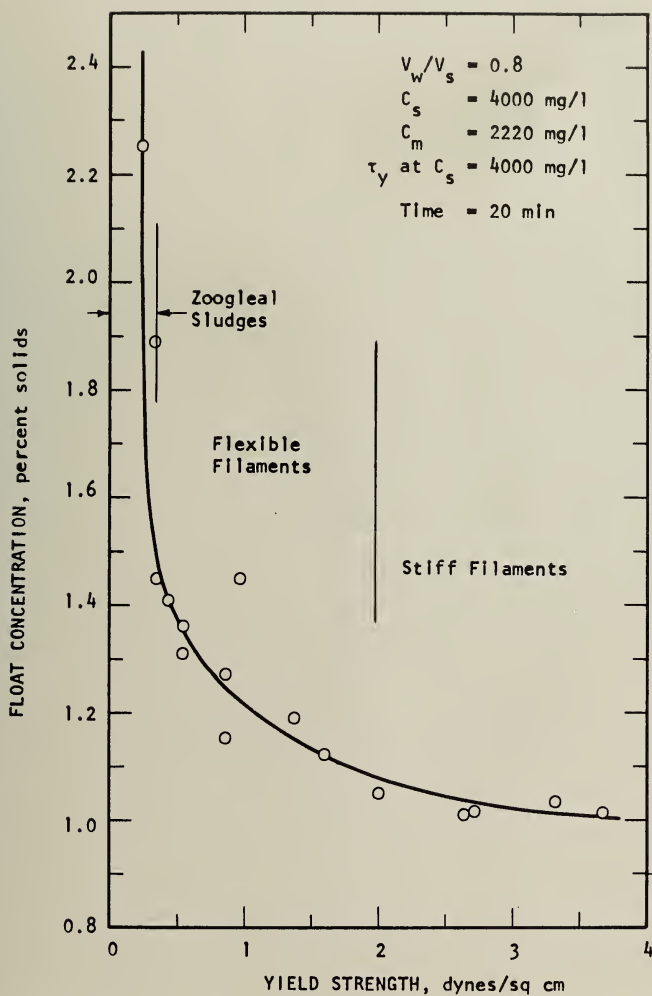


FIGURE 39. RELATIONSHIP BETWEEN SLUDGE YIELD STRENGTH AND FLOAT CONCENTRATION FOR BATCH FLOTATION TESTS

that wall effects are factors to be considered, especially in small columns, with filamentous sludges, checks made using a larger column indicated that apparently at the relatively low solids concentrations in the flotation tubes, the results were not appreciably influenced by wall effects. The data presented in Figure 39 are considered to be a reliable indicator of the effect of yield strength on the float concentration.

The data show that as the yield strength of the sludge increased the float concentration which was obtained in the batch flotation test decreased. This trend was also observed in the continuous laboratory flotation unit. The curve in Figure 39 can be divided into three different sections based upon the types of organisms which determined the yield strengths of the sludges. The first section including the range of yield strengths from about 0 to 0.35×10^{-2} dynes/sq cm represents the zooglear sludges. The section spanning from about 0.36×10^{-2} to 2.0×10^{-2} dynes/sq cm represents the partially zooglear sludges and the filamentous growths where the filaments are somewhat flexible, such as the string-of-beads type, for example. The section from about 2×10^{-2} dynes/sq cm on up is for those sludges comprised of stiff filaments such as the Caryophanon-like sludges and the straight smooth rigid filaments mentioned earlier. It is indeed interesting to note that the sludge having the long, stiff filaments, which has been somewhat of a "spoiler" in almost every other plot where it has been included, plots very nicely here along with the other high yield strength sludges. Apparently the presence of relatively few of this type of filament markedly influenced the rheological properties and flotation behavior of the sludge.

When the plastic viscosity data were plotted against the float concentration data, a curve having the same general shape as the yield strength vs float concentration plot resulted. These data are shown in Figure 40. The reason for the similarity in shapes stems from the fact that, in general,

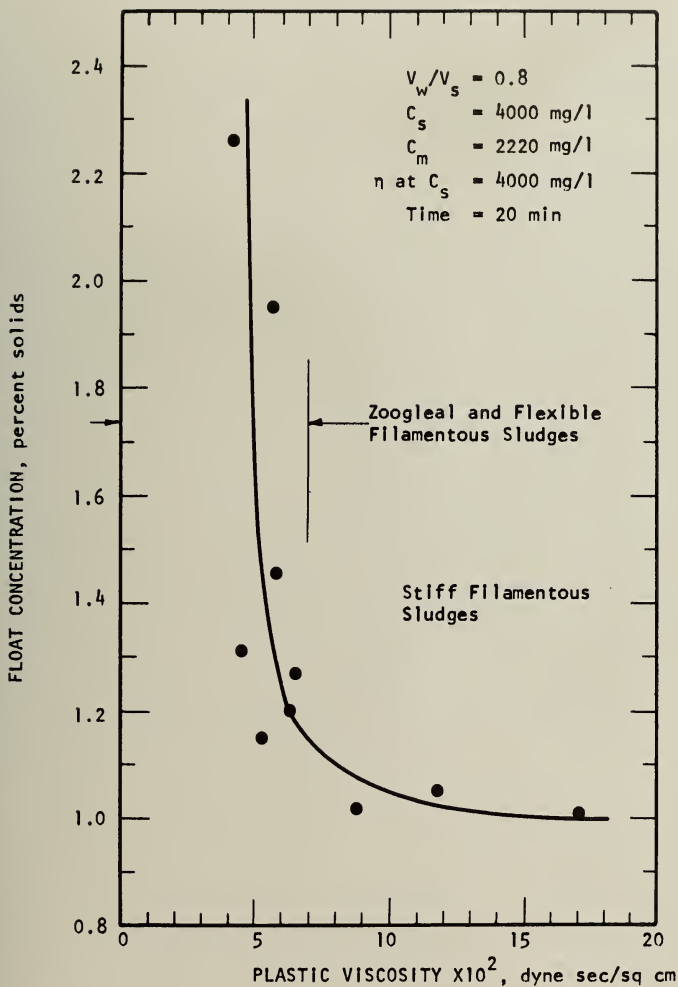


FIGURE 40. RELATIONSHIP BETWEEN PLASTIC VISCOSITY AND FLOAT CONCENTRATION

sludges having high yield strengths have higher plastic viscosities than the lower yield strength sludges. The plot may be divided into two sections. The section from 0 to about 7×10^{-2} dyne sec/sq cm includes both the zooglear and flexible filamentous sludges. The section from 7×10^{-2} dyne sec/sq cm on up represents the more rigid filamentous sludges.

The effects of the rheological properties of the sludges upon the batch flotation rise rates are shown in Figures 41 and 42. The rise rates were inversely related to the yield strengths of the sludges. A fairly good curve can be drawn through the points representing sludges having yield strengths less than 0.5 dynes/sq cm. Figure 41 can be divided into three sections, 0 to 0.25, about 0.26 to 0.40, and about 0.41 to 1.0 dyne/sq cm for the zooglear, flexible filament and stiff filament containing sludges respectively. The curve resulting from the plotting of rise rate vs plastic viscosity had a similar shape but showed more scatter in the data points.

It should be pointed out that the rheological properties discussed above have been made using activated sludges without the presence of the air bubbles which are attached to the sludge particles during the flotation test. Therefore, the rheological measurements made were intended only to provide a quantitative means of characterizing the sludge.

Attempts were made to measure the rheological properties of the float using the rotational viscometer. A problem encountered here made reliable determinations impossible. As the sludge was transferred to the viscometer, some of the entrained air was stripped out. While being sheared in the viscometer the sludge was continuously having air stripped from it which resulted in decreasing values of torque as the shearing continued. The data which were obtained indicated that float with the air entrained may have a somewhat higher plastic viscosity than the same float with the air stripped

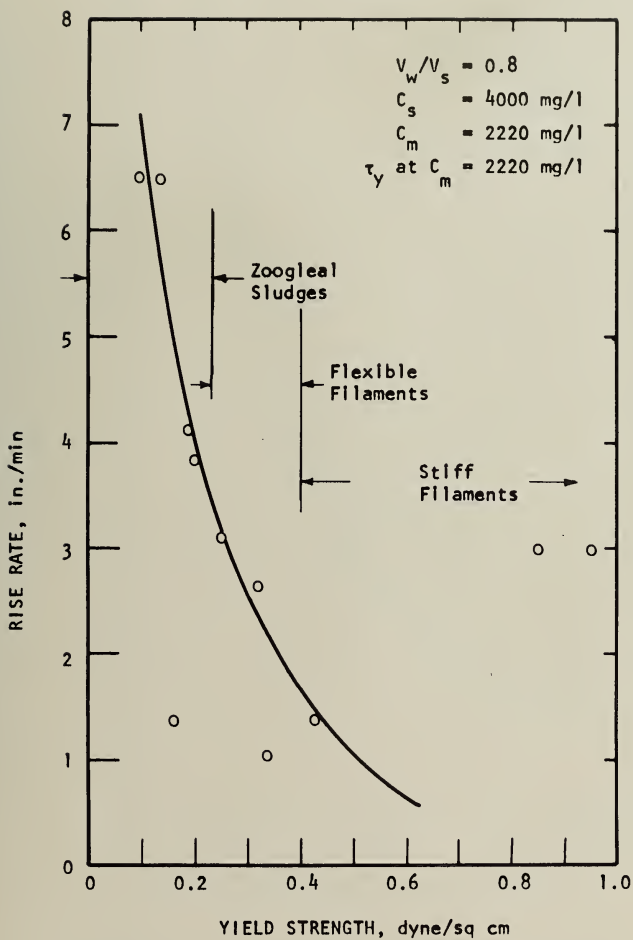


FIGURE 41. RELATIONSHIP BETWEEN YIELD STRENGTH AND RISE RATE

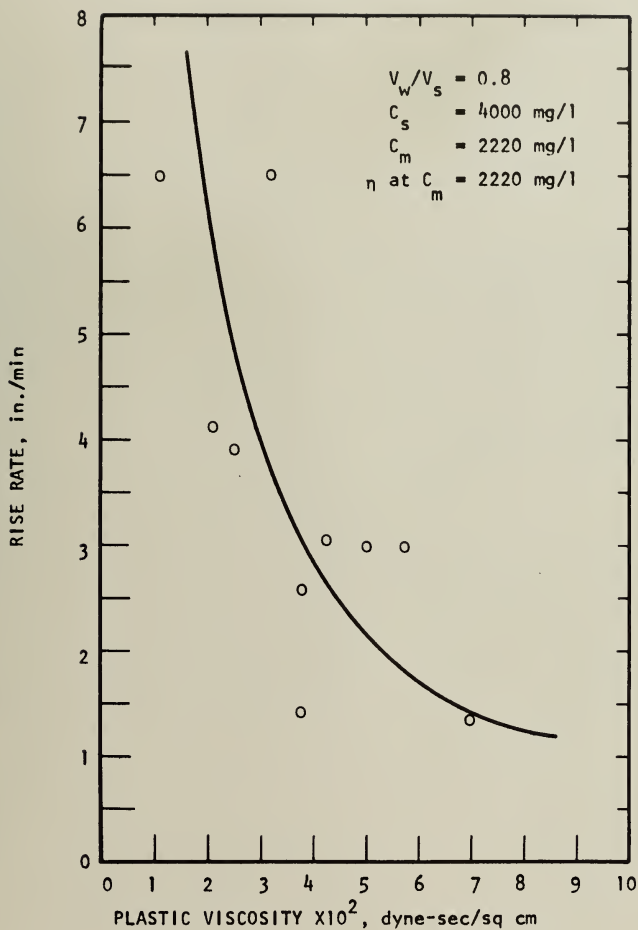


FIGURE 42. RELATIONSHIP BETWEEN RISE RATE AND PLASTIC VISCOSITY

out of it. This would be expected since the air bubbles adsorbed to the sludge floc result in agglomerates which have properties somewhat different than those of the sludge floc alone. The volumetric concentration of the sludge floc would be increased and, although Einstein's law does not hold for the sludges at high concentrations, it does indicate that plastic viscosity would increase as the volumetric solids concentration increased. The yield strengths were found to be comparable.

It should be pointed out at this point that in plotting the float concentration and rise rates as functions of a single parameter such as yield strength or plastic viscosity it was tacitly assumed that the other parameter remained constant. Sufficient data is not available to permit the construction of families of curves such as curves for yield strength vs float concentration for constant plastic viscosity or vice versa.

7. Continuous Flotation Unit Performance

The continuous laboratory unit was used in the experimental work primarily as a means of separating the activated sludge solids so that they could be recycled to the aeration tank in order to maintain a continuous process. Data were not routinely taken from it as a part of the main experimental work. Some float concentration data were collected, however. There were a number of operational variables which influenced the performance of the continuous flotation unit, the effects of which can be noted in the concentration of float which was obtained. Among these variables were the air to solids ratio, the recycle rate, the solid and liquid loading rates applied to the unit, and the speed, depth of skimming, and operating cycle of the float scrapers. During the course of the months that the experimental work was carried out, these variables were changed a number of times. Often these changes were made out of necessity in order to keep the unit operating so

that continuous solids separation could be maintained. Therefore, it was not possible to maintain any one set of operational conditions from which comparisons of the floatability of the sludges of various characteristics could be made. Some float concentration data were collected, however. The float concentration data which coincided with the rheological data which were taken have been plotted and are presented in Figure 43. The data obtained from the batch flotation tests has been plotted on the same figure for purposes of comparison. Despite the changes in operational variables which were made in the continuous unit from time to time it is indeed interesting to note that the plots of yield strength vs float solids concentration for the continuous unit and for the batch tests are essentially identical.

8. Summary

The microorganisms which predominated in the activated sludge systems employed in this study shifted unpredictably during the course of the work. The shifts were believed to have resulted from the forces of population dynamics. The operating problems encountered in trying to maintain steady state conditions may have contributed to these shifts but are not considered to be a major cause.

The relationship between the nitrogen content of the sludge and the flotation parameters and between the C/N ratio of the sludge and the flotation parameters were only general in nature. As the percentage of nitrogen increased and the C/N ratio decreased, the float concentration and rise rates tended to increase. There were valid exceptions to that general rule which made the use of the nitrogen content and the C/N of the sludges unreliable as indicators of flotation behavior.

There was no apparent relationship between the amount of extracellular polysaccharide which could be stripped from the sludge by blending and

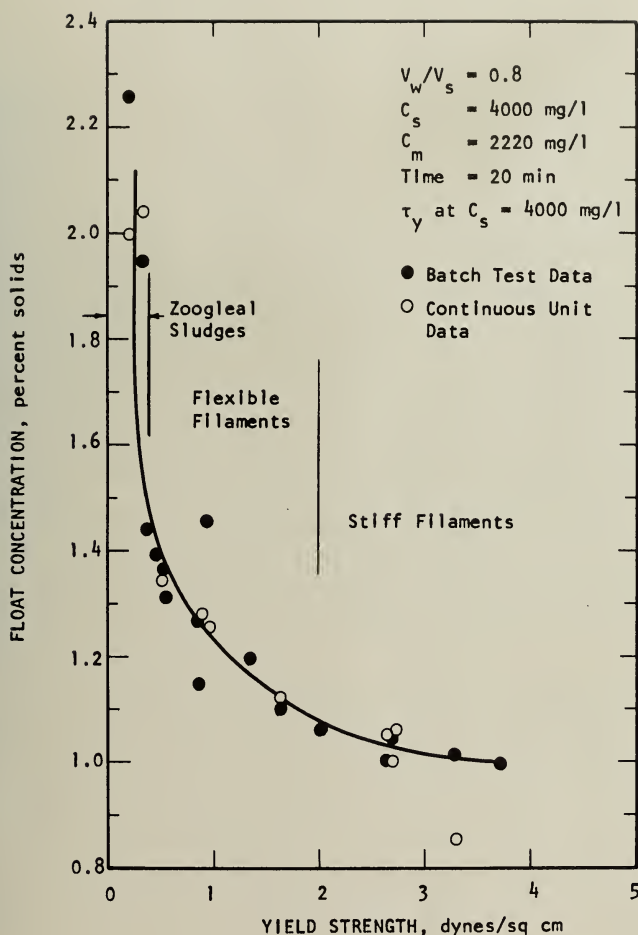


FIGURE 43. RELATIONSHIP BETWEEN SLUDGE YIELD STRENGTH AND FLOAT CONCENTRATION FOR CONTINUOUS FLOTATION UNIT

the flotation characteristics of the sludge. The amount of polysaccharide stripped varied inversely with the nitrogen content of the sludge.

The rheological properties of the sludge were found to be the most useful parameters for relating sludge characteristics to flotation behavior. This was as might be expected since the flotation behavior of the sludge is determined by the physical characteristics of the sludge and the rheological properties are measures of the physical and morphological characteristics of the suspension. The rheological properties of the sludges varied with the changes in the morphology of the sludges, with the stiff filamentous sludges giving yield strengths which were an order of magnitude greater than those of the zooglear sludges at comparable solids concentrations. The plastic viscosities varied directly with the yield strengths. The yield strengths of the sludges were found to increase as the nitrogen content of the sludges decreased as long as they did not exceed 1.5 dynes/sq cm. At higher yield strengths there seemed to be no relationship. The plastic viscosity varied inversely with the nitrogen content.

The rheological data correlated well with the batch flotation data, particularly with the float concentration data. The lower yield strength sludges gave higher float concentrations. Since the yield strength is a measure of the resistance to compaction it is reasonable that a relationship would exist between yield strength and float solids concentration. A similar relationship was found to exist between float concentration and plastic viscosity. The plots where yield strength and plastic viscosity were plotted against rise rate gave curves very similar in shape and again showed that the lower yield strength sludges floated more quickly. Float solids data collected from the continuous laboratory flotation unit when plotted against the

yield strength data gave a curve which was essentially identical to the curve obtained from the batch flotation tests.

B. Batch Flux Analysis of Continuous Thickener Operation

1. General

The batch flux plot provides a convenient method for analyzing and predicting the performance of continuous sedimentation basins and thickeners. This method has been promoted and used in the design and analysis of gravity thickeners (Dick 1970a, 1970b) but, to this author's knowledge, has never been applied to flotation processes. Since flotation is essentially sedimentation in reverse, it would seem that this method of analysis should be applicable to flotation.

This method is based upon the concept that in a suspension each layer of different concentration has a certain capacity to transmit solids to the next layer of higher concentration. If the rate at which solids are supplied to a layer exceeds the layer's capacity to transfer them, the layer then increases in thickness and limits the operation of the thickener. The limiting layer can be determined by use of the data obtained from a series of batch tests made using a range of concentrations of sludge which would include the concentration of the limiting layer.

The solids flux is defined as the weight of solids which can pass through a unit area in a unit of time. For a batch process the flux is obtained using the following equation (Dick, 1970):

$$G_b = C_i V_i \quad (17)$$

where

G_b = batch flux

C_i = initial concentration of solids in
terms of wt/unit volume

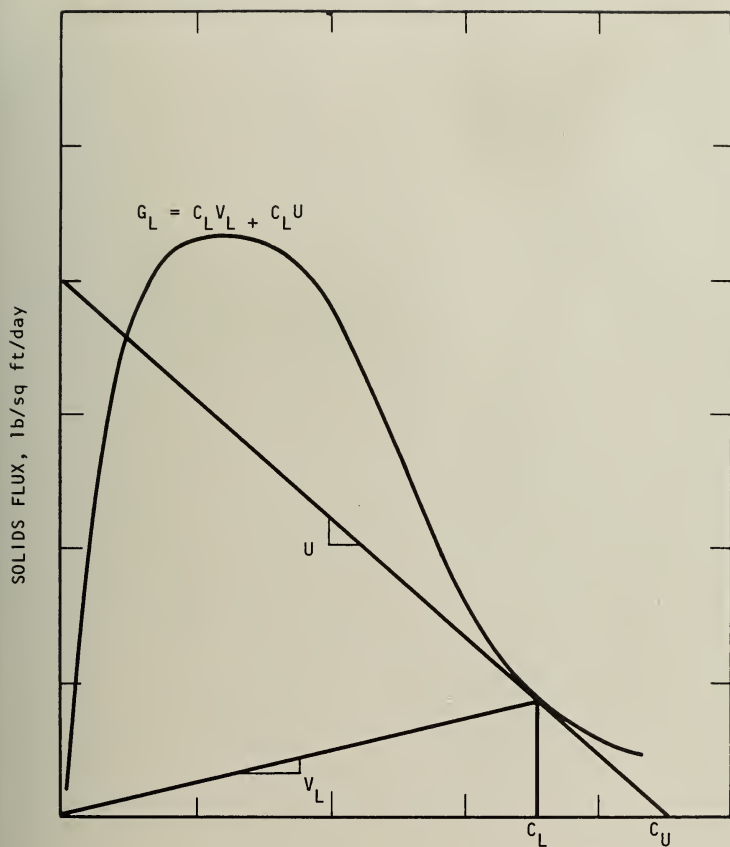
V_i = interfacial velocity

The flux curve is drawn by plotting the values of batch flux against the concentrations for which they were determined. A typical flux plot is shown in Figure 44. Straight lines drawn tangent to the flux plot and connecting the two axes represent the operating conditions of a continuous thickener. The slope of the line is the withdrawal velocity of the thickened sludge having concentration C_u , where C_u is the intercept of the abscissa when the applied flux is G_L , the intercept of the ordinate. The concentration represented by the point of tangency is that of the limiting layer.

The flux curve can be used both for design of thickeners and in the analysis of the performance of existing ones. When used in design several alternative designs can easily be considered by drawing a number of tangents to the flux curve. Similarly, the flux plot can be used to evaluate the effects of operational changes upon thickener performance.

2. Comparison of Batch Flux Results With Laboratory Flotation Unit Data

In this work the batch flux curve was tested to see if this method of analysis could be used to predict the operation of continuous flotation units. The batch flux curves were constructed from data obtained from batch rise rate tests which were performed over a range of solids concentrations. The batch testing procedure described in the previous chapter was used. The air to solids ratio was kept constant for all tests made in any particular run. The air to solids ratio used in the batch tests were the same as that of the continuous unit. The tests were run in 3.5 and 7.5 in. diameter columns. The flux applied to the continuous flotation unit and the float solids concentrations were known. The rise rates obtained for the batch tests performed at pressures greater than 40 psig were multiplied by the appropriate correction factors to bring them all to the common base of 40 psig. The correction factors were based on the data of Figure 10. The factors were 1.35,



SUSPENDED SOLIDS CONCENTRATION, mg/l

FIGURE 44. METHOD OF DETERMINING LIMITING CONDITIONS

1.80 and 3.26 respectively for pressures of 60, 80, and 120 psig. An operation line drawn from the flux axis tangent to the batch flux curve gave the predicted float solids concentration at the intersection of the suspended solids axis. The predicted float concentration was then compared with the actual values obtained from the continuous flotation unit. A typical batch flux plot constructed from batch flotation test data is shown in Figure 45.

A summary of the data obtained from a number of runs is presented in Table 5. In the first several runs which were made the flux curves were not extended far enough so that the limiting solids concentration could be reached. As a result the flux plots did not reach values as low as the applied flux so, of course, it was impossible to determine a predicted float concentration. These runs were made at the air to solids ratios between 0.006 and 0.0109 using maximum pressures of 80 psig. The data for these curves are not shown. By increasing the maximum pressure of saturation to 120 psig and reducing the air to solids ratio to 0.0046 it was possible to extend the solids flux curve far enough that a limiting concentration could be reached. A graphical comparison of the actual float concentrations obtained from the continuous flow flotation unit and the values predicted by the batch flux analyses is presented in Figure 46. These data indicate surprisingly good agreement in several cases. This is especially true when the number of factors influencing the results of the batch flotation tests and the magnitude of the correction applied for the differences in pressures of saturation are considered. For some values the agreement was not as good. The lack of agreement in these cases may be due to the effects of the many factors which influence the test results.

The two cases where the predicted float concentrations greatly exceeded the actual concentrations obtained, that is, batch flux curves 5 and

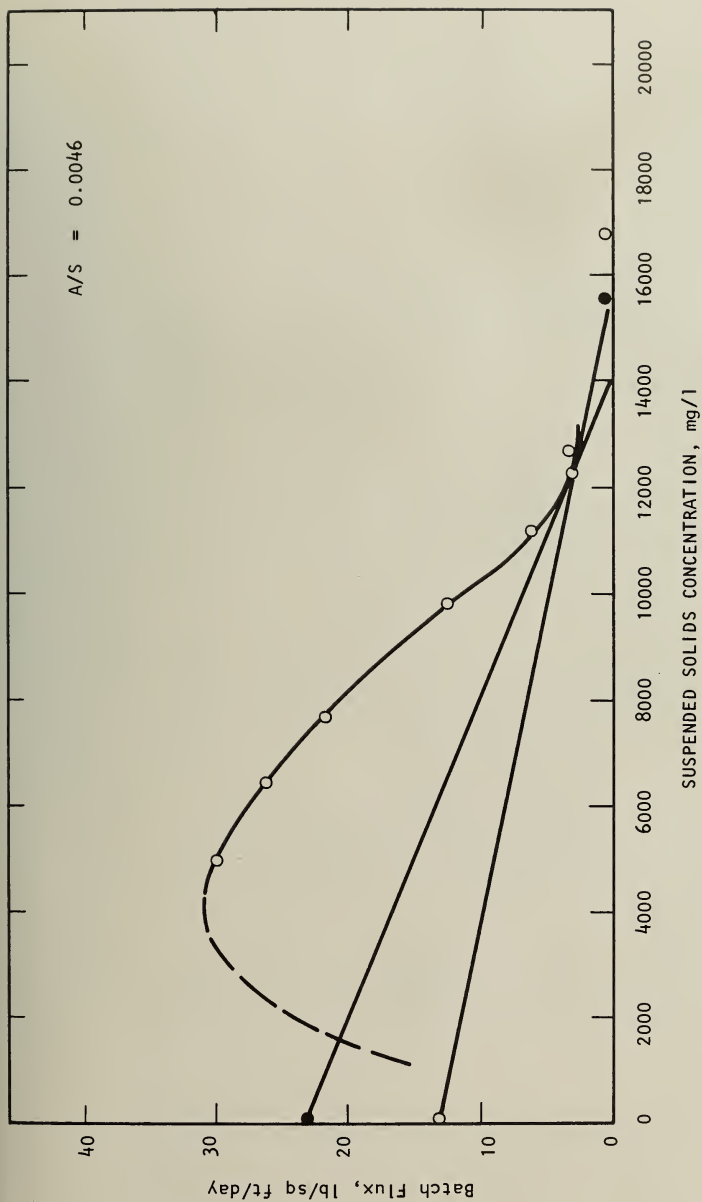


FIGURE 45. TYPICAL BATCH FLUX PLOT FOR THE LABORATORY CONTINUOUS FLOTATION UNIT

TABLE 5

SUMMARY BATCH FLOTATION DATA

Batch Flux Curve	(A/S) _B	(A/S) _C	Continuous Unit		Batch Flux Analysis Percent Solids	Deviation of Actual Conc from Predicted Conc Percent
			Applied Flux lb/sq ft/day	Float Conc Percent Solids	Float Conc Predicted by Batch Flux Analysis Percent Solids	
1	0.0046	0.0048	18.4	21,000	17,800	15.2
	0.0046	0.0046	19.5	17,200	17,200	0
2	0.0046	0.0045	19.0	19,400	15,400	26
	0.0046	0.0043	15.6	15,400	16,000	3.9
3	0.0046	0.0052	23.1	15,500	14,200	8.4
	0.0046	0.0040	13.3	16,800	16,200	3.6
4	0.0046	0.0045	15.5	15,800	16,000	1.3
5	0.0046	0.0046	24.4	12,300	18,300	49
6	0.0057	0.0057	19.1	14,400	30,000	108
7	0.0109	0.0109	14.4	18,600	---	--

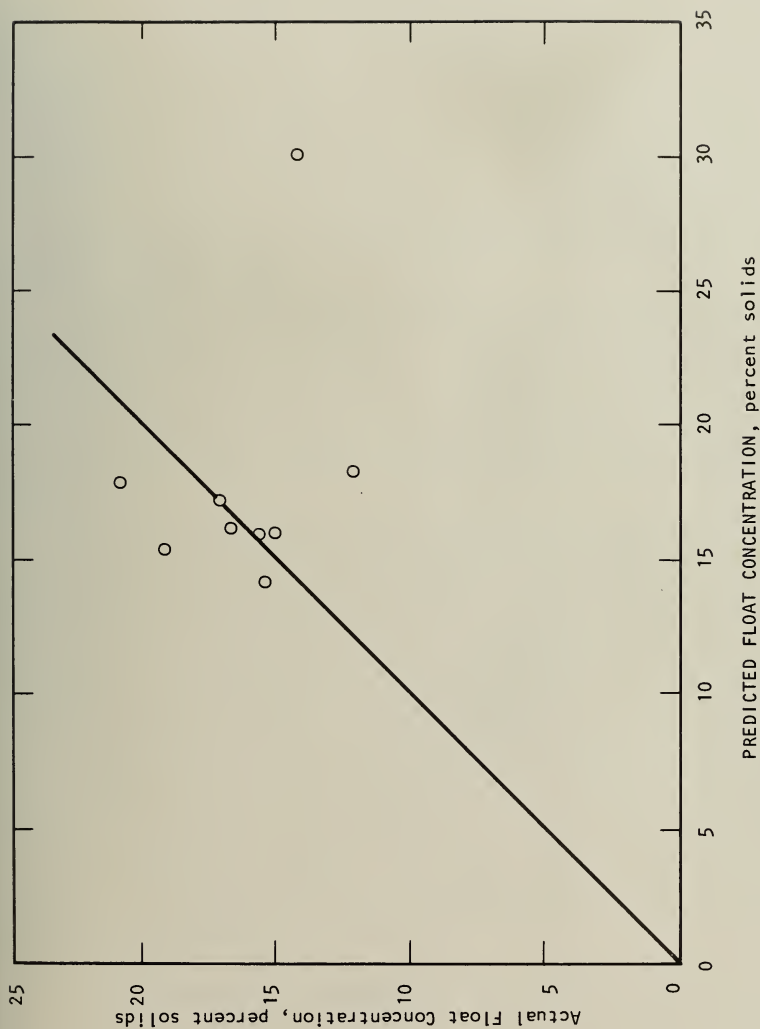


FIGURE 46. COMPARISON OF PREDICTED FLOAT CONCENTRATIONS WITH THE ACTUAL FLOAT CONCENTRATIONS OBTAINED FROM THE CONTINUOUS FLOW FLOTATION UNIT

6, may have resulted from instances when the continuous floatation unit was underloaded. With the flotation unit operating at a given sludge withdrawal rate underloading would result in a float concentration which is less than the maximum obtainable. The cases where the float obtained was more concentrated than predicted cannot be explained by underloading. Some of the variation in the data may be due to the fact that the flotation unit may not always have been operated at the conditions which would give the maximum float solids concentrations.

The fact that the laboratory continuous flow flotation unit was not hydraulically nor geometrically a model of a real full-scale unit and is rather a toy in comparison may also help to explain the fact that the solids flux curve did not always accurately predict the float solids obtained from the unit.

In the batch flotation tests using the most concentrated sludges long lag periods were noted between the time of column filling and the time when an observable interface was formed. It seemed possible that during this long lag period the microorganisms in the sludge might be reducing the flotation driving force by consuming the oxygen present in the supplied air. In order to determine if this might be the case the continuous flotation unit was operated on nitrogen gas while the batch tests for the solids flux curve were also performed using nitrogen. The results of that series of tests are listed as Run 4 in Table 5 and are essentially the same as those run using air as the agent of flotation.

It was desired that the continuous flotation unit could be operated over a fairly wide range of solids fluxes so that the operating lines drawn between the fluxes and the resulting float concentrations could be treated as tangents and permit the construction of the actual solids flux curve which

would define the continuous unit's operation. On a number of occasions attempts were made to obtain these data; but, at best, they were only partially successful. The problem here was to maintain a constant air to solids ratio while manipulating the applied flux.

With the flotation unit being used as a clarifier, the float solids, after being collected, were recycled back to the aeration tank. Any adjustment in the operating parameters of the flotation unit which would result in a change in the volume of return sludge would also result in more feed being discharged to the flotation unit. The attaining of a constant air to solids ratio was a trial and error procedure.

3. Investigation of Possible Methods for Extending the Batch Flux Plot

a. Direct Pressurization

The possibility of using direct pressurization of the sludge itself as a means of extending the flux curve to higher concentrations was explored. With this method the mixed liquor would be aerated and saturated with air under pressure and then released to the flotation chamber. This was tried and compared with the standard method of performing the batch test. A standard flotation test was performed using a sludge which gave a blended suspended solids concentration of about 7,200 mg/l. The sludge to be directly pressurized was diluted to give it a concentration of 7,200 mg/l. The sludge was then pressurized at a pressure which would result in an air to solids ratio similar to that of the standard test. The sludge, upon floating, gave a rise rate that was more than twice as fast as that for the sludge which was floated in the standard way. The interface was harder to distinguish and the supernatant was more turbid than with the standard test. Since the rise rates were so different for the two methods and the interface was very poorly defined, direct pressurization could not be used as a means of extending the flux curve.

While the direct pressurization technique does not represent what is usually done in full scale flotation units which are used to thicken waste activated sludge, it does make one wonder if this could not be done in practice. The supernatant is, of course, more turbid; but if this were recycled through the plant it might not be too much of a problem.

b. Talmadge and Fitch Method

Talmadge and Fitch (1955) developed a method based upon the Kynch analysis which made it possible to develop the solids flux plot from one batch settling test rather than from a multiple batch test procedure. Their reasoning was that since all layers having a concentration greater than the layers above them will ultimately propagate to the liquid interface, the interfacial settling velocity for a layer of any given concentration can be determined from the slope of tangents drawn to the sludge interface-time curve. The sludge concentration associated with any given slope can be determined by extending the tangent back to the axis where time is zero. Since by the time a layer of any concentration has propagated to the surface all the solids in the column have passed through that layer, the concentration at any height can be determined using the following formula:

$$C_1 = \frac{C_o H_o}{H_1} \quad (18)$$

where

C_1 = concentration at height H_1

C_o = initial concentration before separation commences

H_o = initial depth of sludge in column

H_1 = depth of sludge at the time being considered

This method was tried using laboratory grown sludges with the hope that it might provide a means for extending the flux curve. The type of results obtained when this method was applied to batch rise rate data is shown in Figure 47. As can be seen from this plot, this is not a satisfactory method for extending the flux curve. If the method were applicable for use with this kind of sludge the batch flux curves calculated from the different rise rate curves should be essentially identical. The failure of the flux curves to match results from the fact that the characteristics of activated sludge differ from those of the ideal suspension assumed in the Kynch analysis upon which this procedure was based. The ideal suspension of the Kynch analysis was considered to be one in which the particles were rigid, spherical, uniform in size and shape and evenly distributed in any horizontal plane. Activated sludge is made up of non-rigid, flocculent, non-spherical particles which are not necessarily uniform in size nor shape. Additionally, the flocs form aggregates and structures which possess yield strengths (Dick, 1965).

4. Effect of Anaerobic Conditions Upon Flotation

When dealing with aerobic activated sludges it is important that the sludge be kept aerobic until its use in the batch flotation test if the rise rates obtained are to represent what happens in flotation of the aerobic sludge. An experiment was performed in order to determine the magnitude of the effect of anaerobic conditions upon rise rate. A sludge sample was collected and one float test was performed shortly after collection. The remainder of the sludge was divided with one half being aerated while being held and the other being permitted to enter anoxic conditions. Tests were performed several hours later and the rise rates of the sludges were compared. The rise rate for the unaerated sludge, after 6 hrs, had dropped from the initial value of 15 ft/day to 6.6 ft/day while the aerated sample had a rise

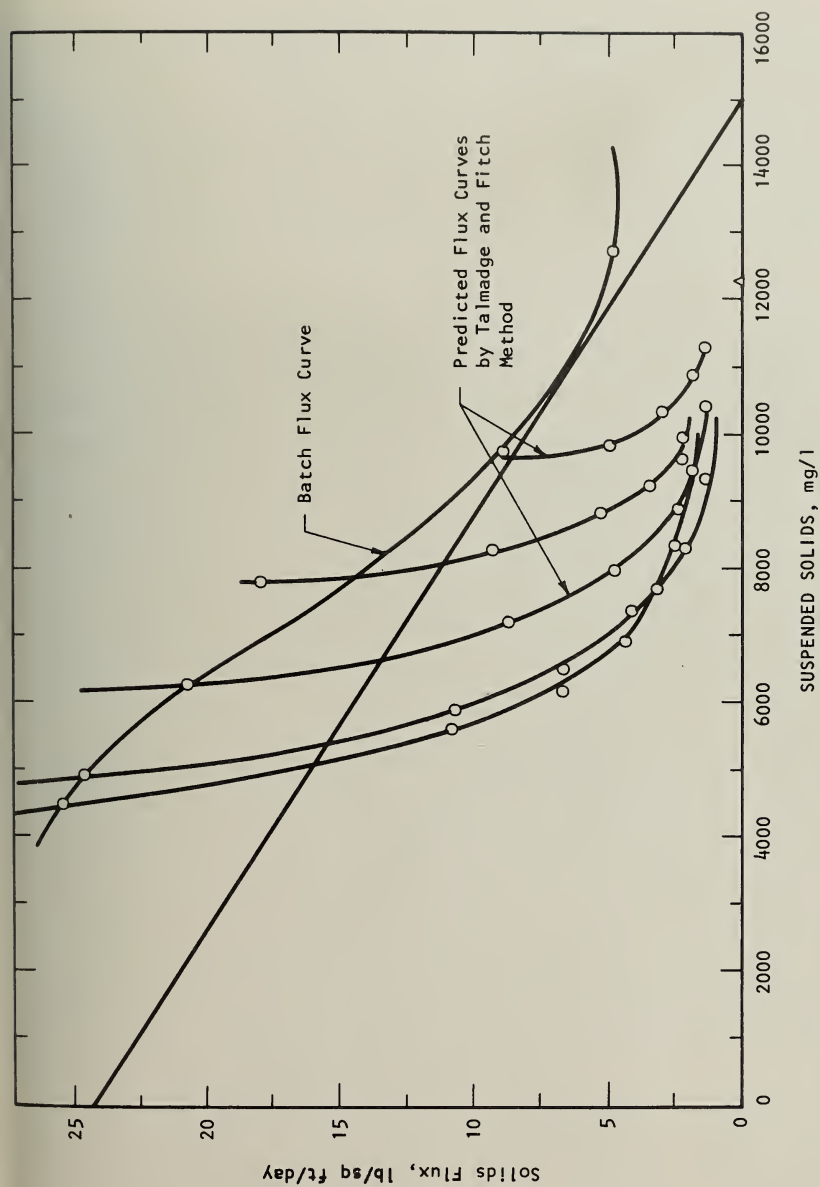


FIGURE 47. TALMADGE AND FITCH EXTENSION OF BATCH FLUX CURVE

rate of 17.3 ft/day. The data clearly shows that being held without aeration results in reduced rise rates when the sludge was subsequently floated. This was probably due at least in part to the utilization by the microorganisms of the oxygen in the air attached to sludge particles. Changes may also have taken place in the surface properties of the sludge due to the anoxic conditions.

5. Summary

In theory the batch flux analysis should be applicable to use with flotation units as well as with gravity thickeners. One serious problem in the development of the flux curve is the difficulty encountered in obtaining blended suspended solids concentrations high enough to equal or exceed the limiting solids concentration. Pressures of saturation higher than those normally employed in flotation were used to extend the flux plot to higher sludge concentrations. The rise rate values obtained at the higher pressures were adjusted to compensate for the loss in rise rate associated with the use of the higher pressures. In view of the number of factors which influence the batch flotation test results and considering the magnitudes of the correction factors which were applied to account for the effect on rise rates of changing pressures of saturation, surprising agreement between the predicted and actual values of float concentration were obtained in several cases. In about an equal number of instances, however, good correlation was not obtained. The reasons for the lack of agreement probably stem from the many factors which influence the batch flotation test and the possibility that the continuous flotation unit was underloaded in some cases.

The Talmadge and Fitch method was not a satisfactory means for extending the flux curve for the type of sludges used in this study. Direct pressurization of the sludge gave rise rates in excess of those obtained using

the standard batch flotation procedure. For that reason and also because of the poorly defined interface formed, it did not provide a good means for extending the curve. The batch flux analysis was found to be somewhat limited in its usefulness in predicting the float concentrations obtainable from continuous flotation units. The necessity of applying correction factors to compensate for the effect of column diameter, sludge height, and changes in the pressure of saturation, together with the need for relatively large volumes of sludge in order to determine the effects of column diameter, and the difficulty in extending the curve made the use of this method somewhat less attractive than it originally appeared to be.

C. Significance of Results

The success of the flotation process as a means of solids separation is dependent upon the properties of the material to be floated. This investigation has included the study of some properties of bulked sludges and has related these properties to the flotation behavior. This contribution of information to the meager amount in this area should be helpful to those confronted with the problem of separating bulked sludges. The good relationship which was shown to exist between the flotation behavior and the rheological properties suggests their use as an aid in predicting flotation unit performance.

Batch flotation tests are usually performed for the purpose of evaluating the flotation characteristics of the sludge or other material to be floated prior to the design and installation of a flotation unit. The rate of separation and the concentration of solids obtained in the float are the two main parameters considered. Some of the significant findings of this research relate to the identification of a number of factors which influence the results of batch flotation tests. The consideration of the effects of

flotation column diameter, column depth and column filling time should lend improvement to results which are obtained from batch flotation test procedures. The introduction of a method of performing the batch flotation test which more closely parallels the process which takes place in continuous flow units should improve flotation test results.

The information provided here regarding the effects of saturation pressure upon rise rates points out the importance of this parameter in the flotation process.

Consideration of the several factors mentioned here should result in the obtaining of better information upon which flotation units may be designed.

V. CONCLUSIONS

1. The results of the batch flotation test procedure are influenced by the column filling time, the column diameter and the column depth. The magnitude of these effects upon the interfacial rise rate is dependent upon the solids concentration and characteristics of the sludge.
2. Data obtained using the method which is commonly in use in practice may give inaccurate results because the factors mentioned previously which influence the test results are not generally taken into consideration.
3. A technique for performing batch flotation tests which is believed to more closely represent the process in a continuous flotation unit was developed. This method gives better flotation results than the commonly used method, especially with highly bulked sludges.
4. A retardation factor exists in batch flotation tests similar to that which exists in sedimentation. The magnitude of the retardation factor is dependent upon the solids concentration and the physical properties of the sludge.
5. Filamentous sludges can be floated to concentrations of at least one percent solids by dissolved air flotation. The maximum applied loading rate must be kept lower in some cases than for the zoogeal sludges.
6. The carbon to nitrogen ratio and the nitrogen content of the sludge are not reliable indicators of the flotation behavior of the sludge.
7. The carbon to nitrogen ratio and the nitrogen content of the sludge correlate well with the plastic viscosity of the sludge. The relationship between yield strength and the carbon to nitrogen ratio and the nitrogen content of the sludge are not well defined.
8. The rheological properties of the sludge, yield strength and plastic

viscosity are the best means of characterizing bulked sludges and of relating the sludge properties to its flotation behavior.

The yield strengths of the sludges are dependent upon the morphological characteristics of the organisms making up the sludges.

The amount of strippable extracellular polysaccharide present in the sludge does not appear to have any influence upon the flotation behavior of the sludge.

In view of all the factors which influence its results, the batch flux analysis gives surprisingly accurate predictions of the float solids concentrations obtained from the laboratory continuous flow flotation unit on several occasions. The fact that in other instances the predicted and actual do not agree is probably due to the many factors which influence batch flotation tests.

The pressure at which the recycle water is saturated was found to greatly influence the flotation rise rate of the sludge. The rise rate decreases exponentially as the pressure increases even though the air to solids ratio is held constant and the possibility that in some cases the continuous flotation unit may have been underloaded.

The use of a number of pressures of saturation as a means of extending the batch flux curve gives good results as long as the rise rates are corrected to account for the loss in rise rates due to the use of the higher pressures. The precision with which the blending operation can be performed together with the necessary but undesirable extrapolation of the data to obtain the correction factors will limit the magnitude of the pressures which will be of practical use.

The Talmadge and Fitch method of analysis is an unsatisfactory method for extending the batch flux curve, at least for filamentously bulked sludges.

The coaxial cylinder rotational viscometer is not suitable for determining the rheological properties of the floated sludge because the loss of the air bubbles from the float while in the viscometer gives changing values of torque at constant shear rate.

VI. SUGGESTIONS FOR FUTURE WORK

On the basis of the results of this study and observations made during the course of the investigation, it is suggested that further investigation should be pursued in the following areas:

1. A study of the surface properties of activated sludges and their influence upon the efficiency of air bubble attachment and the subsequent flotation of the sludge should be made. This would involve the development of a method for measuring the efficiency of bubble attachment.
2. A study of the influence of the dissolved organic material present in the suspending liquid upon the flotation behavior of activated sludge should be made. It was observed in the course of the current study that the addition of primary sewage effluent to the aeration tank for a period of an hour or two markedly improved the flotation characteristics of poorly floating sludges. Information which would explain the reason for this would be enlightening.

REFERENCES

- Bechir, M. H. and Symons, J. M. 1966. "The Effect of Nitrogen Deficiency on the Behavior of the Complete-Mixing Activated Sludge Process," Air and Water Pollution International Journal 10:191.
- Bhatla, M. N. 1967. "Relationship of Activated Sludge Bulking to Oxygen Tension," Journal of the Water Pollution Control Federation 39:1978.
- Bloodgood, D. E. 1947. "Concentration of Activated Sludge," Sewage Works Journal 19:202.
- Cassell, E. A., Sulzer, F. T., and Lamb, J. C. 1966. "Population Dynamics and Selection in Continuously Mixed Cultures," Journal of the Water Pollution Control Federation 38:1398.
- Chakrabarti, S. K. 1968. "Changes in Some Physical Properties of Activated Sludge Under Different Biological Conditions," Master's Thesis, University of Illinois, Urbana, Illinois.
- Clifford, W. and Windredge, M. E. D. 1932. "The Settlement of Activated Sludge," Proceedings of the Institute of Sewage Purification 115.
- Cole, R. F. 1969. "Experimental Evaluation of the Kynch Theory," Doctoral Thesis, University of North Carolina, Dissertation Abstracts 29:4687B.
- Conrad, H. E. 1969. Private Communication.
- Dick, R. I. 1965. "The Applicability of Prevailing Gravity Thickening Theories to Activated Sludge," Doctoral Thesis, University of Illinois, Urbana, Illinois.
- Dick, R. I. 1970a. "Thickening," In Gloyna, E. F. and Eckenfelder, Jr., W. W. (ed) Water Quality Improvement by Physical and Chemical Processes, University of Texas Press, Austin, Texas.
- Dick R. I. 1970b. "Role of Activated Sludge Final Settling Tanks," Journal Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 96:423.
- Dick R. I. and Ewing, B. B. 1967. "The Rheology of Activated Sludge," Journal of the Water Pollution Control Federation 39:543.
- Dobias, B. and Vinter V. 1966. "Flotation of Microorganisms," Folia Microbiologica 11:314.
- Eckenfelder Jr., W. W., Rooney, T. F., Burger, T. B. and Gruspier, J. T. 1956. "Studies on Dissolved Air Flotation of Biological Sludges," In McCabe, B. J. and Eckenfelder, Jr., W. W., Biological Treatment of Sewage and Industrial Wastes, Vol. II, Reinhold, New York.

- Ettelt, G. A. 1964. "Activated Sludge Thickening by Dissolved Air Flotation," Proceedings 19th Industrial Waste Conference, Purdue University.
- Farnsworth, G. A. 1967. "The Effect of Induced Flocculation on Settling and Thickening Behavior of Activated Sludge," Masters Thesis, University of Illinois, Urbana, Illinois.
- Ford, D. L. and Eckenfelder, W. W. 1966. "The Effect of Process Variables on Sludge Floc Formation and Settling Characteristics," The University of Texas Center for Research in Water Resources Technical Report to the Public Health Service EHE-11-6604.
- Freidman, B. A., Dugan, P. R., Pfister, R. M., Remsen, C. C. 1968. "Fine Structure and Composition of the Zooglear Matrix Surrounding Zooglear ramigera," Journal of Bacteriology 96:2144.
- Garwood, J. 1967. "Polyelectrolytes in Sewage Treatment," Effluent and Water Treatment Journal 7:380.
- Gaudy, A. F., Jr. 1962. "Colorimetric Determination of Protein and Carbohydrate," Industrial Water and Wastes 7:17.
- Gaudy, E. and Wolfe, R. S. 1962. "Composition of an Extracellular Polysaccharide Produced by Sphaerotilus natans," Applied Microbiology 10:200.
- Gaudin, A. 1967. Flotation, Second Edition, McGraw-Hill, New York, N. Y.
- Gaudin, A. M., Fuerstenau, M. C. and Mitchell, S. R. 1959. "Effect of Pulp Depth and Initial Pulp Density in Batch Thickening," Mining Engineering 11:613.
- Genetelli, E. J. and Heukelekian, H. 1964a. "The Effect of Chemical Composition of Substrate and Loading on the Performance and Bulking of Activated Sludge," Journal of the Water Pollution Control Federation 36:643.
- Genetelli, E. J. and Heukelekian, H. 1964b. "Components of the Sludge Loading Ratio and Their Effect on the Bulking of Activated Sludge," Proceedings 19th Industrial Wastes Conference, Purdue University.
- Gratteau, J. C., and Dick, R. I. 1968. "Activated Sludge Suspended Solids Determination," Water and Sewage Works 115:468.
- Greeley, S. A. 1945. "The Development of the Activated Sludge Method of Sewage Treatment," Sewage Works Journal 17:1135.
- Green, H. 1949. Industrial Rheology and Rheological Structures, John Wiley, New York.
- Greenburg, A. E., Klein, G., and Kaufman, W. J. 1955. "Effect of Phosphorous on the Activated Sludge Process," Sewage and Industrial Wastes 27:277.
- Haseltine, T. R. 1932. "The Activated Sludge Process at Salinas, California, with Particular Reference to Causes and Control of Bulking," Sewage Works Journal 4:461.

- Haseltine, T. R. 1938. "The Use of Hydrated Lime in the Activated Sludge Process," Sewage Works Journal 10:1017.
- Helmers, E. N., Frame, J. D., Greenberg, Sawyer, C. N., 1951. "Nutritional Requirements in the Biological Stabilization of Industrial Wastes, III, Treatment with Supplemental Nutrients," Sewage and Industrial Wastes, 24:496.
- Heukelekian, H. 1941. "Activated Sludge Bulking," Sewage Works Journal 19:39.
- Heukelekian, H. and Weisberg 1956. "Bound Water and Activated Sludge Bulking," Sewage and Industrial Wastes 28:558.
- Hoover, S. R. and Porges, P. 1949. "Treatment of Dairy Wastes by Aeration - II: Continuous Aeration Studies," Proceedings of the Fifth Industrial Wastes Conference, Purdue University.
- Jorne, W. R., Hartman, H. E., Rinanca, U. S., and St. Clair, R. L. 1962. "Biological Treatment of Fine Chemical Plant Wastes," Journal of the Water Pollution Control Federation 34:833.
- Kurwitz, E. and Katz, W. J. 1959. "Concentrating Activated Sludge to a Fuel Value of 4,000 BTU per Gallon," Wastes Engineering 30:730.
- Langols, R. S. and Heukelekian, H. 1939. "Studies on Activated Sludge Bulking," Sewage Works Journal 11:927.
- Langols, R. W. and Heukelekian, H. 1940. "Studies on Activated Sludge Bulking II, Bulking Induced by Domestic Sewage," Sewage Works Journal 12:703.
- Jones, P. H. 1964. "The Effect of Temperature and Oxygen Tension on One of the Microorganisms Responsible for Sludge Bulking," Proceedings of the 19th Industrial Waste Conference, Purdue University.
- Jones, P. H. 1965. "The Effect of Nitrogen and Phosphorus Compounds on One of the Microorganisms Responsible for Sludge Bulking," Proceedings 20th Industrial Waste Conference, Purdue University.
- Jones, P. H. 1966. "Experiments with Bulking Sludge and its Ability to Degrade High Carbohydrate Wastes and Sulphite Waste Liquor," Pulp Paper Magazine Canada 67, No. C T-139-T-145 (Convention Issue 1966).
- Jones, W. H. 1968. "Dissolved Air Flotation Thickening of Waste Water Sludges," Presented at Nebraska Water Pollution Control Association, Great Plains Design Conference, Omaha, Nebraska.
- Juni, E. and Heym, G. A. 1964. "Pathways for Biosynthesis of a Bacterial Capsular Polysaccharide, IV. Capsule Resynthesis by Decapsulated Resting-Cell Suspension," Journal of Bacteriology 87:461.
- Kalyuzhnyi, M. Y., Petrushko, G. M. and Novikova, G. P. 1965. "Flocculation of Candida utilis and Candida tropicalis Yeast Cells and its Relation to Flotation," Mikro biologiia 34:800.

- Kammermeyer, K. 1941. "Settling and Thickening of Aqueous Suspensions," Industrial and Engineering Chemistry 32:1484.
- Katz, W. J. 1958. "Sewage Sludge Thickening by Flotation," Public Works 89:114.
- Katz, W. J. 1959. "Adsorption - Secret of Success in Separating Solids by Dissolved Air Flotation," Wastes Engineering 30:374.
- Katz, W. J. and Geinopolos, A. 1963. "Dissolved Air Flotation as a Method of Thickening Aerobic Biological Solids," Paper presented at the High Level Conference on Sludge Dewatering, University of Michigan, Ann Arbor, Michigan, Jan. 30, 1963.
- Katz, W. J., and Geinopolos, A. 1967. "Sludge Thickening by Dissolved Air Flotation," Journal of the Water Pollution Control Federation 39:946.
- Katz, W. J. and Geinopolos, A. 1968. "Concentration of Sewage Treatment Plant Sludges by Thickening," Proceedings of the Tenth Sanitary Engineering Conference, University of Illinois, Urbana, Illinois, Feb. 6 and 7, 1968.
- Kaylor, F. B., Bechir, M. B., and Symons, J. M. 1963. "Atmospheric Nitrogen Fixation in Activated Sludge," Proceedings 18th Industrial Wastes Conference, Purdue University, 1963.
- Keefer, C. E. and Meisel, J. 1955. "Activated Sludge Studies," Sewage and Industrial Wastes 27:982.
- Keefer, C. E. 1963. "Relationship of Sludge Density Index to the Activated Sludge Process," Journal of the Water Pollution Control Federation 35:1166.
- Kraus, L. S. 1949. "Quantitative Relationships in the Activated Sludge Process," Sewage Works Journal 21:613.
- Lackey, J. B. and Wattie, E. 1940. "Studies of Sewage Purification, XIII. the Biology of *Sphaerotilus natans kutzing* in relation to Bulking of Activated Sludge," Sewage Works Journal 12:669.
- Logan, R. P. and Budd, W. E. 1955. "Effect of BOD loadings on Activated Sludge Plant Operation," In McCabe, B. J. and Eckenfelder, Jr. W. W., (ed), Biological Treatment of Sewage and Industrial Wastes, Pergamon Press, N.Y. 1955.
- Luderitz, O., Staub, A. M., and Westphal, O. 1966. "Immunochemistry of O and R Antigens of Salmonella and Related Enterobacteriaceae," Bacteriological Review 30:192.
- Ludzack, F. J., Schaffer, R. B., and Ettinger, M. B. 1961. "Temperature and Feed as Variables in Activated Sludge Performance," Journal of the Water Pollution Control Federation 33:141.
- Mancini, J. L. 1962. "Gravity Clarifier and Thickener Design," Proceedings of the 17th Industrial Wastes Conference, Purdue University.

- Mayo, W. E. 1965. "Industrial Waste Application of Dissolved Air Flotation," Presented at Annual Meeting of Water Pollution Control Federation, Atlantic City, N. J.
- McWhorter, T. R. and Heukelekian, H. 1964. "Growth and Endogenous Phases in the Oxidation of Glucose," Advances in Water Pollution Research, McMillan Co. 2:419.
- Morgan, E. H. and Beck, A. J. 1939. "Carbohydrate Wastes Stimulate Growth of Undesirable Filamentous Organisms in Activated Sludge," Sewage Works Journal 1:46.
- Mulbarger, M. C., and Huffman, D. D. 1970. "Mixed Liquor Solids Separation by Flotation," Journal of Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 96:861.
- Nishikawa, S. and Kuriyoma, M. 1968. "Studies on Mucilage in Activated Sludge," Journal of Fermentation Technology 46:381.
- Pipes, W. O. and Jones, P. H. 1963. "Decomposition of Organic Wastes by Sphaerotilus," Biotechnology and Bioengineering 5:287.
- Pipes, W. O. 1967a. "Types of Activated Sludge Which Separate Poorly," Paper Presented at the 40th Annual Meeting, Central States Water Pollution Control Association, June 14, 1967.
- Pipes, W. O. 1967b. "Bulking of Activated Sludge," Advances in Applied Microbiology, Academic Press, Vol. 9:185.
- Pipes, W. O. 1968. An Atlas of Activated Sludge Types, Department of Civil Engineering, Northwestern University.
- Ruchhoft, C. C. and Watkins, J. H. 1929. "Bacteriological Isolation and Study of the Filamentous Organisms in the Activated Sludge of Des Plaines River Sewage Treatment Works," Sewage Works Journal 1:52.
- Ruchhoft, C. C. and Smith, R. S. 1939. "Changes in Characteristics of Activated Sludge Induced by Variations in Applied Load," Sewage Works Journal 11:409.
- Sawyer, C. N. 1966. "Bulking of Activated Sludge and Related Problems," The Activated Sludge Process in Sewage Treatment Theory and Application, University of Michigan Department of Civil Engineering, Feb. 1966.
- Shell, G. L. 1970. Private Communication.
- Smit, J. 1934. "Bulking of Activated Sludge-Causative Organisms," Sewage Works Journal 6:1041.
- Smith, R. S. and Purdy, W. C. 1936. "The Use of Chlorine for the Correction of Sludge Bulking in the Activated Sludge Process," Sewage Works Journal 8:223.

- Snell, F. D. and Snell, C. T. 1961. Colorimetric Methods of Analysis, Vol. 3, D. Van Nostrand Co. Inc., Princeton, New Jersey.
- Standard Methods for the Examination of Water and Wastewater, 1965. 12th Edition, American Public Health Association.
- Symons, J. M. and McKinney, R. E. 1957. "The Biochemistry of Nitrogen in the Synthesis of Activated Sludge," Sewage and Industrial Wastes 30:874.
- Szaniszlo, P. J. 1968. "Production of a Capsular Polysaccharide by a Marine Filamentous Fungus," Journal of Bacteriology 95:1474.
- Talmage, W. P. and Fitch, E. B. 1955. "Determining Thickener Unit Areas," Industrial and Engineering Chemistry 47:38.
- Tapleshay, J. A. 1945. "Control of Sludge Index by Chlorination of Return Sludge," Sewage Works Journal 17:1210.
- Tagiguchi, Y. 1968. "Studies on Mucilage in Activated Sludge, (I) On Characteristics of the Mucilage and its Production," Journal of Fermentation Technology 46:488.
- Tagiguchi, Y. 1968. "Studies on the Mucilage in Activated Sludge, (II) On Correlation Between Viscosity of the Mucilage and Settling Characteristics of Activated Sludge," Journal of Fermentation Technology 46:497.
- Tischler, L. F. and Eckenfelder, W. W. 1968. Linear Removal of Simple Organic Compounds in the Activated Sludge Process, The University of Texas Center for Research in Water Resources, Technical Report to the FWPCA, EHE-12-6702 CRWR-22.
- Vesilind, P. A. 1968. "The Influence of Stirring in the Thickening of Biological Sludge," Doctoral Dissertation, University of North Carolina, Chapel Hill, N. C.
- Vrablik, E. R. 1959. "Fundamental Principles of Dissolved Air Flotation of Industrial Wastes," Proceedings of the 14th Industrial Waste Conference, Purdue University.
- Walters, C. F. 1966. "Biochemical Storage Phenomena in Activated Sludge," Doctoral Thesis, University of Illinois, Urbana, Illinois.
- Wang, R. C. T. 1967. "A Viscometer for the Study of the Rheology of Activated Sludge," Unpublished Project Report, University of Illinois.
- Weinshank, D. J. and Garver, J. C. 1967. "Theory and Design of Aerobic Fermentations," In Pepler, H. J. (ed) Microbial Technology, Reinhold Publishing Co.
- Wilkinson, J. F. 1958. "The Extracellular Polysaccharides of Bacteria," Bacteriological Reviews 22:46.
- Wyss, O. and Morland, E. J. 1968. "Composition of Obligate Hydrocarbon-Utilizing Bacteria," Applied Microbiology 16:185

APPENDIX

Typical calculations of continuous flow flotation unit operating conditions:

Dilution Water Flow Rate, $Q = 3,530 \text{ ml/min}$

Substrate Feed Rate, $g = 20 \text{ ml/min}$

Sludge Recycle Rate, $Q_{SR} = \frac{29.5}{3.5} \frac{1}{\text{min}} = 8.43 \text{ ml/min}$

Flow Rate to Flotation Unit, $Q_F = 3,530 + 20 + 843 = 4,393 \text{ ml/min}$

Clarified Liquid Discharge from Flotation Unit, $E = 6,000 \text{ ml/min}$

Liquid Recycle Rate = $E - Q = 6,000 - 3,530 = 2,470 \text{ ml/min}$

Mixed Liquor Suspended Solids = 4.0 g/l

Gas Release Rate = $42 \text{ ml wet gas/l recycle}$

Vol Dry Air = (vol wet air) $\left(\frac{\text{std temp}}{\text{gas temp}} \right) \left(\frac{\text{atm pressure} - \text{vapor pressure}}{\text{std atm pressure}} \right)$

$$= (42 \text{ ml air/l recycle}) \left(\frac{273^\circ}{295.5^\circ} \right) \left(\frac{750 \text{ mm Hg} - 20.4 \text{ mm Hg}}{760 \text{ mm Hg}} \right)$$

= $37.4 \text{ ml dry gas at STP/l recycle water}$

$Wt = (0.0374 \text{ l}) (1.2929 \text{ g/l})$

= $0.0484 \text{ g air/l recycle water}$

$A/S = \frac{(0.0484 \text{ g air/l recycle}) (2.47 \text{ l/min})}{(4.393 \text{ l/min}) (4.0 \text{ g/l})}$

= $0.0068 \text{ g air/g solids}$

Loading Rate = $\frac{(4.393 \text{ l/min}) (4 \text{ g/l}) (1440 \text{ min/day})}{(454 \text{ g/lb}) (3.3 \text{ sq ft})}$

= $16.9 \text{ lb/sq ft/day}$

VITA

Robert Frank Wood was born September 14, 1937, in Eddington, Maine and was graduated from Brewer High School, Brewer, Maine, in 1954.

He received his B.S. Engr. degree from Walla Walla College, College Place, Washington, in 1960. From 1960 to 1965 he was employed as a sanitary engineer with the Division of Sanitation and Engineering of the Oregon State Board of Health in Eugene and Portland, Oregon.

He received his M.S. degree in Environmental Health Engineering from the University of Texas at Austin in 1966. He was a Federal Water Pollution Control Trainee from 1966 to 1970. He will become Assistant Professor of Environmental Health at Loma Linda University in September, 1970.

He is a member of the American Water Works Association and the Water Pollution Control Federation and is a Registered Professional Engineer in Oregon.



UNIVERSITY OF ILLINOIS-URBANA



3 0112 032384742